Department of Natural Resources and Mines
Geological Survey of Queensland

Queensland Minerals and Energy Review

Mapping of Surat Basin coal seam gas reservoir units

L.C. Cranfield

Queensland Government

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Disclaimer:
The Surat Basin Mapping Project is an Industry Priorities Initiative funded by the Future Resources Program of the Department of Natural Resources and Mines (DNRM) to improve scientific knowledge of gas reservoirs in the Surat Basin. It is a joint project between industry and Government (the Geological Survey of Queensland (GSQ)), to enhance the work done by coal seam gas companies and the Office of Groundwater Impact Assessment (OGIA). The primary industry proponent was Origin Energy.

Len Cranfield of Cranfield Geological Services International (CGSI) was engaged by Origin Energy to update existing surface geology mapping within the Surat Basin with a focus on the Walloon Coal Measures (WCM) and Springbok Sandstone (SBKS) in both outcrop and subcrop, as well as the overlying alluvium. The analyses, interpretation and mapping contained in the maps and the accompanying report have been based on digital geological data from various sources including airborne geophysical data, satelite imagery, borehole logs, chemical and mineralogical analyses. While care has been taken by CGSI to ensure the accuracy of the information provided in this report and geological maps, users must make their own assessment of the suitability of information, digital data and interpretation. The data gathered in this project has been used by the GSQ to produce new geological maps of the Surat Basin.

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Cover photographs: Top: Panorama of road cutting of mudstone and cross-bedded sandstone (Springbok Sandstone); bottom left: Sandstone pavement in Springbok Sandstone with intercalated mudstone; bottom right: Grey-brown, intercalated lithic labile crossbedded sandstone and mudstone of the Eurombah Formation.

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Summary

The Surat Basin coal seam gas (CSG) reservoir units mapping project focuses on identifying subcrop boundaries between Cainozoic cover (including alluvial and colluvial units of the 'Condamine Basin') and duricrust above the stratigraphic section from the upper Hutton Sandstone / upper Marburg Subgroup to the top of the Springbok Sandstone.

The section includes the Eurombah Formation, Walloon Coal Measures and Springbok Sandstone, overlain by Main Range Volcanics, duricrust, Tertiary consolidated sediments (Ts), Chinchilla Sand (Tc), and surficial Tertiary and Quaternary units (TQf, TQs, TQr/b, Qa/b and Qa). The method of defining the boundaries of the Mesozoic stratigraphic units included the use of existing mapping, airborne geophysics, coal mine location, augmented SPOT (Satellite Pour l'Observation de la Terre) satellite data, coal resource identification polygons, lithological and wireline logs from stratigraphic, coal, coal seam gas and water bores, company geological mapping of the extent of Walloon Coal Measures and extrapolation of geological boundaries.

Structurally, the Auburn and Yarraman sub-provinces underlie the eastern boundary of the Surat Basin at a shallow depth. Major fault structures including the Goondiwindi – Moonie Fault identified on seismic sections have been extended using interpretation of the available regional magnetic data in conjunction with previous seismic data interpretations.

The Surat Basin thickens markedly to the west of the Burunga – Leichhardt Fault Zone. Major fault structures were interpreted from magnetic data in conjunction with the digital elevation model (DEM) and previous geological mapping, water bore data and isopachs of the Walloon Coal Measures to the west of the Project area. Data from coal exploration boreholes and CSG exploration wells were used to better define the subcrop boundaries on the Chinchilla 1: 250 000 Map Sheet area.

The main mapping tool for identifying different alluvial and colluvial units was the ternary radiometric image. This was backed up by the digital elevation model, previous 1: 250 000 geological mapping and strata logs from water bores.

In the area of interest, the oldest of the alluvial fans that has been dated is the Pliocene Chinchilla Sand (Tc) and the youngest is TQr/b derived from erosion of Cainozoic basalts. TQr/b is a thin clay-rich colluvium that overlies TQs which is a unit of clayey and sandy alluvium derived from erosion of the Marburg Subgroup, Eurombah Formation and Walloon Coal Measures.

The Durabilla Formation has not been formally defined in the Australian Stratigraphic Units Database and there is paucity of consistent criteria to differentiate this formation from the Eurombah Formation; therefore the definition of the Eurombah Formation accepted herein is based on all strata from the sequence from the top of the Hutton Sandstone to the base of the lowermost coal of the Taroom Coal Measures member of the Walloon Coal Measures, and also from the top of the Marburg Subgroup to the lowermost Taroom Coal Measures' coal.

The extent of Cainozoic volcanics of the Main Range Volcanics was interpreted in the outcrop areas and in subcrop beneath the alluvial fans and alluvial deposits, based on an integrated interpretation of radiometric and magnetic images linked to existing regional mapping polygons. From an interpretation of the magnetic data there are both normally and reversely polarised flows indicating a range of ages of the basalts and other volcanic rocks within the Miocene. These flows were apparently erupted from a series of fissure eruptions and from point sources. Comparison with previous mapping, radiometric images and water bore data show there are sills intruding the Mesozoic sequence in addition to the flows.

The output for the project includes two map products at 1:500 000 scale (Appendix 1 and 2) that have been produced in conjunction with this report. These revise the surface geology map and provide a solid geology map focusing on the targeted Mesozoic section. The surface map includes cross sections of various areas across the outcrop and subcrop of the targeted Mesozoic units. The solid geology map shows the interpreted subsurface extent of the targeted units beneath Cainozoic cover of alluvium, alluvial fans and Cainozoic sediments and volcanics.

Appendix 3 provides a rationale for standardisation of picking formations and correlation of a series of CSG wells across the Surat Basin. Appendix 4 provides the results of X-ray fluorescence (XRF) and HyLogger (hyperspectral mineralogical logging) data from selected outcrop and core samples (November 2015 field trip). Appendix 5 provides the photographs of these samples. Appendix 6 provides groundwater database logs of selected water bores from the Condamine Basin and likely correlations with alluvial fan units, Mesozoic units and Cainozoic basalt. Appendix 7 represents the October 2016 field trip which was undertaken to validate the mapping of target formations.

A digital data package has been published and incorporated into the statewide Detailed Geology and is available for viewing from MineOnlineMaps and for downloading from QSpatial: open QSpatial first then follow this link to the report Coal Seam Gas Units 2017 - Northern Surat and Clarence Moreton Basins.

This report includes a recommendation for further work to update the geological mapping for the whole of the Surat Basin using a similar methodology. There are also recommendations for reinterpreting and incorporating soil information from the Department of Natural Resources and Mines (DNRM) into geological map data and use of the structural updates from ongoing research into seismic data over the Surat Basin.

Introduction

The coal seam gas industry has collated new, comprehensive Surat Basin geological datasets through an intensive programme of exploration, appraisal and development. Individual coal seam gas companies have detailed geological conceptualisations at a tenure level; however, geological structures and connectivity are regional in nature. The project requires regional scale collation and interpretation of data for geological / reservoir evaluation, resource development and impact assessment at a basin level. This new data has highlighted major inconsistencies in interpretations between company geology and the available surface geological mapping (Australia 1:250 000 Geological Series).

As part of the 2015 round of the Industry Priorities Initiative under the Future Resources Program of the Department of Natural Resources and Mines, a proposal by Origin Energy and other coal seam gas companies to sub-divide and then map the Injune Creek Group (Figure 1) of the Surat Basin was submitted and accepted. The companies involved in the project for a new geological map include Origin Energy (sponsor), Arrow Energy, Santos, Senex and Queensland Gas Company (QGC). Support was also provided by the Office of Groundwater Impact Assessment (OGIA).

The main deliverables of the project are new surface geological and solid geology maps (Appendices 1 and 2) of the coal seam gas units in the Surat Basin in southern Queensland being the Walloon Coal Measures and Springbok Sandstone and their overlying units. Cranfield Geological Services International (CGSI) was engaged to provide the data to enable an updated geological map to be produced by the Geological Survey of Queensland (GSQ) and to coordinate project planning and outcomes. The project was subdivided into a number of subprojects with a range of specific deliverables.

Issues to be solved in the project are fundamentally linked to defining the sedimentary package containing the producing coal seam gas units of the Surat Basin and their overlying units and include:

- defining the base of the stratigraphic package (the Eurombah / Durabilla formations and whether these represent the same formation)
- how to redefine the Walloon Coal Measures as strictly comprising two coal bearing sequences (the Juandah (upper) and Taroom (lower) coal measures) separated by a sandstone (the Tangalooma Sandstone) and if the Eurombah and Durabilla formations are excluded from the Walloon Coal Measures
- how to separate the Springbok Sandstone and define its extent
- how to define the overlying sediment packages of the Condamine Irrigation Area (the region approximately centred on the Condamine River), its structural evolution and the underlying subcrops of targeted Walloon Coal Measures and Springbok Sandstone
- what is the relationship of the stratigraphy and structure to the methane seeps in the Condamine River.

The key formations comprising the primary focus of the project are the Mesozoic-aged Springbok Sandstone and Walloon Coal Measures, although other work on some overlying and underlying formations was undertaken. This work included examining the lithological and geochemical characteristics of the Westbourne Formation and Hutton Sandstone and the nature of the transition rock units of the Eurombah and Durabilla formations to determine their extent(s); if they are the same lithological formation; and if they are members of the Walloon Coal Measures, separate unique formations or can be merged into a single formation.

The eastern Surat Basin is extensively overlain by Holocene alluvium and colluvium and Cainozoic basalt cover units and has an extensive area of deep weathering. The project was designed in three phases (Phases 1-3) and tested the effectiveness of a desktop study using a range of data sets. Field trips to validate interpretation were scheduled at the completion of Phases 1 and 2.

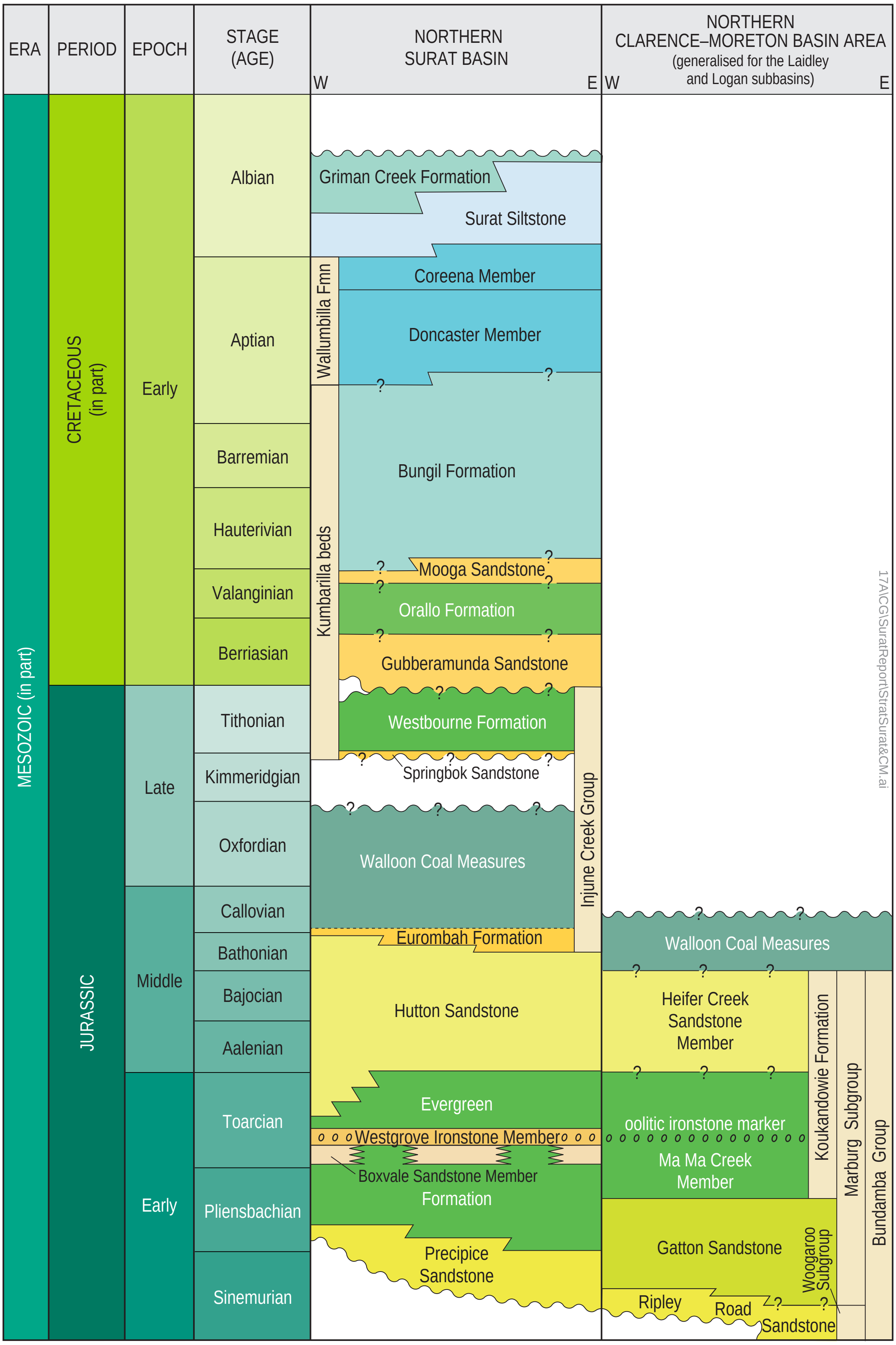


Figure 1. Stratigraphic column—Surat and Clarence-Moreton basins [McKellar, 2017, personal communication and Wainman et al. (2015; for isotopic dating of the Walloon Coal Measures); timescale after Gradstein et al. (2012)].

Phase 1 consisted of testing the effectiveness of updating the existing geological mapping data using remote sensing, airborne geophysics, satellite imagery, the DEM and modelling previously conducted by OGIA. A report was prepared on the standardisation of wireline picks of the formations across the basin by the CSG producing companies (Hauck & Edwards, Appendix 3). This report developed a standardised method for the wireline formation picks for the Westbourne Formation, Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone across the Surat Basin.

Phase 1 was completed in December 2015 following a field excursion investigating outcrop in the Taroom and Roma 1:250 000 Map Sheet areas in November 2015 with updates to the report in 2016. Material collected on the field excursion included field samples for analysis by XRF and HyLogger, field photography and succinct observations of outcrops (Appendices 4 and 5).

Phase 2 focused on defining the boundaries of the Eurombah or Durabilla formations that are transitional between the top of the Hutton Sandstone (and its stratigraphic equivalent in the Clarence–Moreton Basin, the top of the Marburg Subgroup) and the base of the overlying Walloon Coal Measures. The area considered is in the outcrop regions of the Taroom and Roma 1:250 000 Map Sheets and the subcrop area to the south in the Chinchilla, Dalby, Ipswich and Goondiwindi 1:250 000 Map Sheets (Figure 2). This phase was designed to map the Springbok Sandstone and define the overlying cover rocks and unconsolidated Cainozoic cover in these map sheet areas. These boundaries are mostly covered by younger Cainozoic alluvium, colluvium, consolidated sediments and basalt or masked by deep weathering. A desired outcome of the project was the creation of lithostratigraphic boundaries that would intersect with the landscape of the Cainozoic surface cover and define structural corridors that may provide zones of preferential vertical migration of methane to the surface. An important consideration of the subcrop of the targeted formations was identifying the evolution of the Condamine Irrigation Area (informally termed the 'Condamine Basin' here after) and its potential link to methane gas seeps in the Condamine River south of Chinchilla.

This work followed up on the OGIA geological modelling and comprised evaluation of:

- strata, geophysical logs and mapping from coal and coal seam gas drilling, water bores and GSQ stratigraphic boreholes
- regional scale airborne geophysics, in particular the ternary potassium-thorium-uranium (K-Th-U) radiometric image in red, green and blue (RGB) channels and the individual (K, Th, U) channels and magnetic images
- the 1-second DEM to examine topographic trends
- satellite imagery (SPOT data) to assist in extending alluvial areas in conjunction with the DEM and to identify the extent of coal mining operations, and to aid in the extension of alluvial and colluvial areas
- structure contours for the top of Walloon Coal Measures down dip of outcrop
- cover isopachs and structure contours of the depth to the top of the Mesozoic surface beneath the cover of the Condamine Basin based largely on water bore data. The Condamine Basin is a region of intense agricultural development underlying the present drainage system of the Condamine River with a system of alluvial and colluvial sediments and basalt up to 130 m thick.
- Previous geological mapping on the Taroom, Roma, Goondiwindi, Dalby, Ipswich, Chinchilla, Gympie and Mundubbera 1:250 000 Map Sheets
- coal exploration information and maps from Exploration Permits for Coal (EPC) relinquishment reports in the region
- the potential influence of structural dislocations (identifiable from geophysical data) in areas of methane seeps in the Condamine River.

Phase 3 involved the creation of cross sections using a combination of borehole intersections, and minor updates to the current interpretation to fit the validated borehole information. This was followed by a field trip in October 2016 to resolve any anomalies in the location of suspect boundaries. The field trip identified one error of interpretation in the location of the Eurombah Formation, which was amended on the digital and hard copy coverages.

The project required the analysis of borehole and company map data from coal exploration boreholes, coal seam gas exploration and production, wells, water bores and stratigraphic drill holes. It also involved the use of regional scale airborne geophysical data and contoured data linked to key stratigraphic formation tops to support assessment of potential structural dislocation.

Methodology

The methodology adopted for the mapping of the Walloon Coal Measures, Springbok Sandstone and the cover units in the outcrop areas used a combination of radiometric and magnetic images and was outlined in the Phase 1 report.

The available data sets for the project at its commencement were:

1. digitised 1:250 000 scale geology from the Roma, Taroom, Surat, St George, Ipswich, Dalby, Mundubbera, Chinchilla, Gympie, and Goondiwindi Map Sheet areas
2. scanned and geo-rectified 1:250 000 geological mapping raster images over Eddystone, Dirranbandi and Mitchell Map Sheet areas warped to the Spatial Information Resources (SIR) current digital drainage layer
3. ternary radiometric images, rad dose image and individual, K, Th, U data channels
4. magnetic images – first and second vertical derivatives, reduced to the pole (1VD-RTP)
5. 1 sec DEM (DEM gmod Zone 55)
6. Queensland-wide Google SPOT satellite image at a spatial resolution of 10 m, containing spectral bands in the visible red, green, blue spectrum
7. seismic surfaces (Dixon *et al.*, 2011)
8. Spatial Integrated Resources (SIR) datasets for various infrastructure including roads, pipelines, power lines, watercourses and topographic contours (best fit to SPOT). The location of pipelines and powerlines is important as these features are magnetic and may interfere with the interpretation of the magnetic data.
9. air photo coverage of the Ipswich, Chinchilla and Goondiwindi 1:250 000 Map Sheet areas at a scale of 1:85 000, and air photos over the Taroom and Condamine regions at a scale of 1:40 000
10. Neville Exon’s field mapping note book data covering a small area on the Chinchilla 1:250 000 Map Sheet area (sourced from Geoscience Australia)
11. borehole data from GSQ stratigraphic bores, CSG wells and Office of Groundwater Impact Assessment (OGIA) CSG-relevant formation top picks and GIS layers from the OGIA Surat Cumulative Groundwater Model
12. structural boundaries of basins and structural / tectonic provinces standardised from the GSQ Queensland structural boundaries dataset
13. databases of stratigraphic, petroleum, coal seam gas and water bores available from GSQ.

Additional data acquired during the course of the project included a major update to the interpretation of the water bore data of the Condamine Alluvium carried out by Leon Leach of the Department of Science, Information Technology and Innovation (DSITI) which was incorporated into a structural interpretation of this basin. Origin Energy supplied various reinterpretations of CSG borehole data in areas critical to defining subcrop of the targeted units.

A methodology to interpret the extent of the coal seam gas units and their cover rocks was formulated. This methodology included establishing the approximate extent of the cover rocks overlying the key Mesozoic aged units and this was done in a number of stages. The first stage was to reinterpret the OGIA geological boundaries followed by the extent of alluvium and colluvium using the available air photos combined with available radiometrics and the DEM with the SPOT data to extend areas of alluvium where recognised from their geomorphology and from radiometric changes linked to the combined SPOT/DEM images.

Identification of areas of Cainozoic basalt that occurred beyond the currently mapped boundaries of the Main Range Volcanics involved the interpretation of geophysical imagery in conjunction with updating the existing mapping. The geophysical signature of the Cainozoic volcanics showed the occurrence of both normally and reversely polarised flows (indicating different periods of volcanism) and a generally potassic (red) signature in the ternary radiometric image. The magnetic signatures of the basalt were used to extend basalt below mapped Cainozoic cover sediments, and where the magnetic signature of the basalt contrasted with the radiometric signatures of mapped Mesozoic units, intrusive sills were interpreted below the Mesozoic units.

The top of the targeted section (top of Springbok Sandstone/base of the Westbourne Formation) is defined by a thorium (Th) anomaly.

Interpretation of the cover rocks was required to identify extensions of stream alluvium which were added to the map coverage.

Features that were pivotal to the methodology of the project included:

1. Delineating the poorly exposed transitional sedimentary units between the top of the Hutton Sandstone / Marburg Subgroup and the base of the Walloon Coal Measures from inconsistent borehole data and differing interpretation of the stratigraphic succession. This is discussed in the section of the report dealing with the Eurombah Formation and uses a combination of the original regional ground mapping, subtle changes in radiometric pattern and data from water bores and coal exploration mapping.
2. How to successfully redefine the Walloon Coal Measures from the basal coal (of the Taroom Coal Measures) to the top of the unconformity on which the Springbok Sandstone was deposited in outcrop. The mapped base of the unit is determined by a combination of basal coal recognition in coal resource data, locations of existing infrastructure (for potential magnetic signature) as defined by SPOT data, and mapping of the extent of coal resources in relinquishment reports. Extrapolation of the existing borehole data indicates that the Springbok Sandstone unconformity locally erodes the upper section of the Juandah Coal Measures so that in some areas the base of the Springbok Sandstone extends into the lower Juandah Coal Measures. In the outcrop area the base of the Springbok Sandstone was interpreted through a combination of its high relief and higher potassic signature on the ternary radiometric image. This boundary was close to the OGIA boundary in the eastern part of the outcrop area, but was further to the north in the western part of the Taroom Sheet.
3. How to identify where the unconformity at the base of the Springbok Sandstone subcrops below the Condamine Basin. In the subcrop area, it has been based on the definition of coal resource polygons, the depth to SPUNCON (Springbok unconformity) determined by OGIA from borehole data and the presumed higher relief of Springbok Sandstone in contrast to the less resistant coal seams in the Juandah Coal Measures.
4. Obtaining consistent borehole data identifying the top of the Springbok Sandstone below the Westbourne Formation in the deeply weathered area south of the Taroom 1:250 000 Map Sheet area and adjacent to the Condamine Basin. Borehole data using the depth to top of Springbok Sandstone and Westbourne Formation was extrapolated from the outcrop area to subcrop in the south.
5. Defining the subcrop of Cainozoic volcanics in the distributary channels and thickest depositional zone of the Condamine Alluvium. The extent of subcrop of Cainozoic volcanics was identified using the magnetic and radiometric responses of the basalt in the tributary streams to the Condamine System and revealed definite volcanics locally buried below colluvial and alluvial deposits. Water bore data also shows basalt intersections locally greater than 85 m depth in bores penetrating into the Condamine Basin (e.g. water bore registered number 83741 in which the base of the basalt was not reached); however, there is no consistent magnetic signature that would determine the extent of basalt flows in the airborne geophysics due to the regional nature of the data set (400 m line spacing).

6. The difference between the alluvial and colluvial depositional packages of the Condamine Basin. This was determined through a combination of radiometrics, water bore data and the DEM which enabled several units to be defined. The surface expression of the units and their signature is influenced by the source of the sediments of the alluvial and colluvial packages. As these deposits overlap at their margins it is difficult to define the contribution of each to the water bore logs.

7. A series of cross sections (AB to KL) which were developed to validate the mapping at several areas key to the understanding of the location of the targeted formations (see Cross Sections). In addition, the thickness of the cover rocks where interpreted from boreholes was included. To ensure that both cover rocks and Mesozoic stratigraphy were displayed on the section lines a vertical and horizontal exaggeration of 20:1 was employed and the geology of the cross sections was expanded in the body of the report and shown on the surface geological map at 1:500 000 scale (Appendix 1).

The extent of the digital project area includes the Taroom, Mundubbera, Roma, Chinchilla, Dalby, Ipswich, Goondiwindi and Warwick 1:250 000 Map Sheets. The extent of the hard copy maps (Appendices 1 and 2) is more restricted, covering only the extent of subcrop and outcrop of the targeted formations (Figure 2).

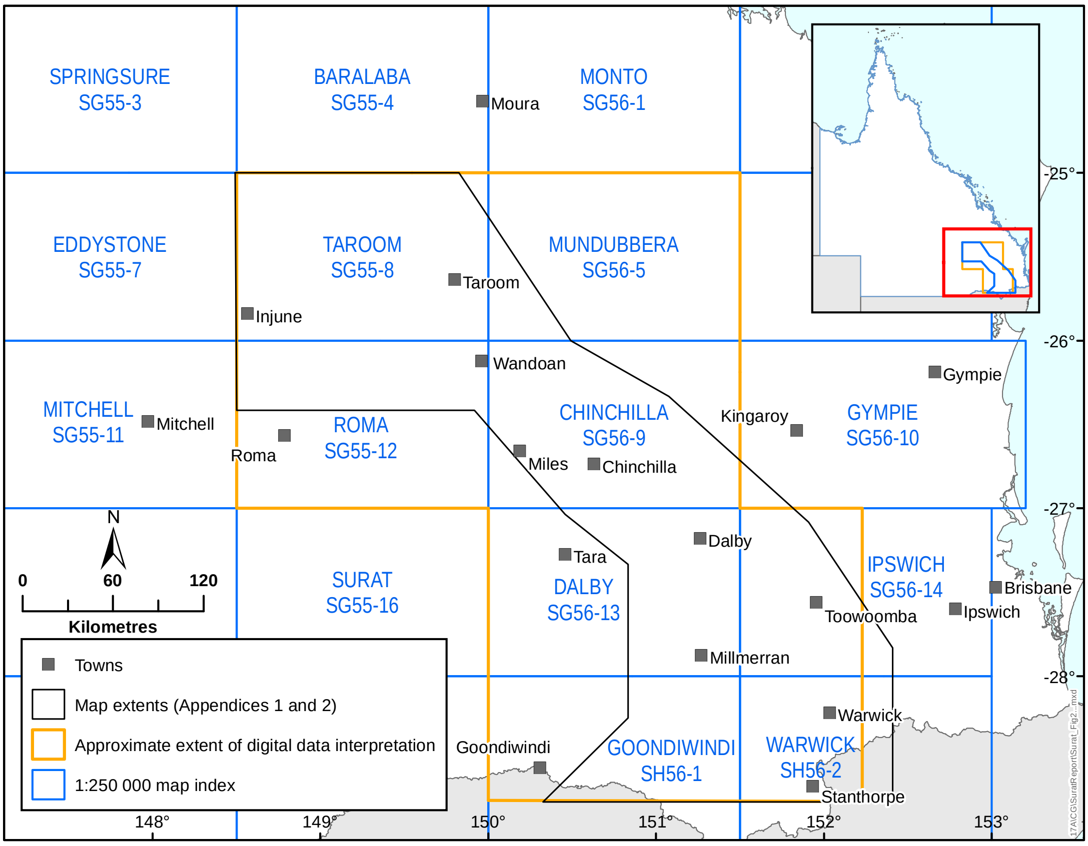


Figure 2. Project area location in relation to 1:250 000 geological map sheets

Structural geology

A regional interpretation of the structure of the Surat Basin was depicted in Exon (1976) who identified that its sediments intertongue with the Clarence–Moreton Basin across the KumbarilIa Ridge. The basin is bounded in the east by the Auburn Arch and the New England Fold Belt; to the west, it intertongues with the Eromanga Basin across the Nebine Ridge (Figure 3). The dominant subsurface feature is the central Taroom Trough, bounded in the east by the Burunga-Leichhardt Fault Zone and the Goondiwindi-Moonie Fault Zone, both of which are thrusts. The effect of the Leichhardt-Burunga Fault can be seen in Cross Sections. Exon (1976) also identified northeast-trending Undulla and Macintyre Faults and the south-southwesterly-plunging Undulla Nose (Figure 3). The Undulla Nose is a feature not readily recognised on the data sets used in this project, but is an important region for CSG exploration.

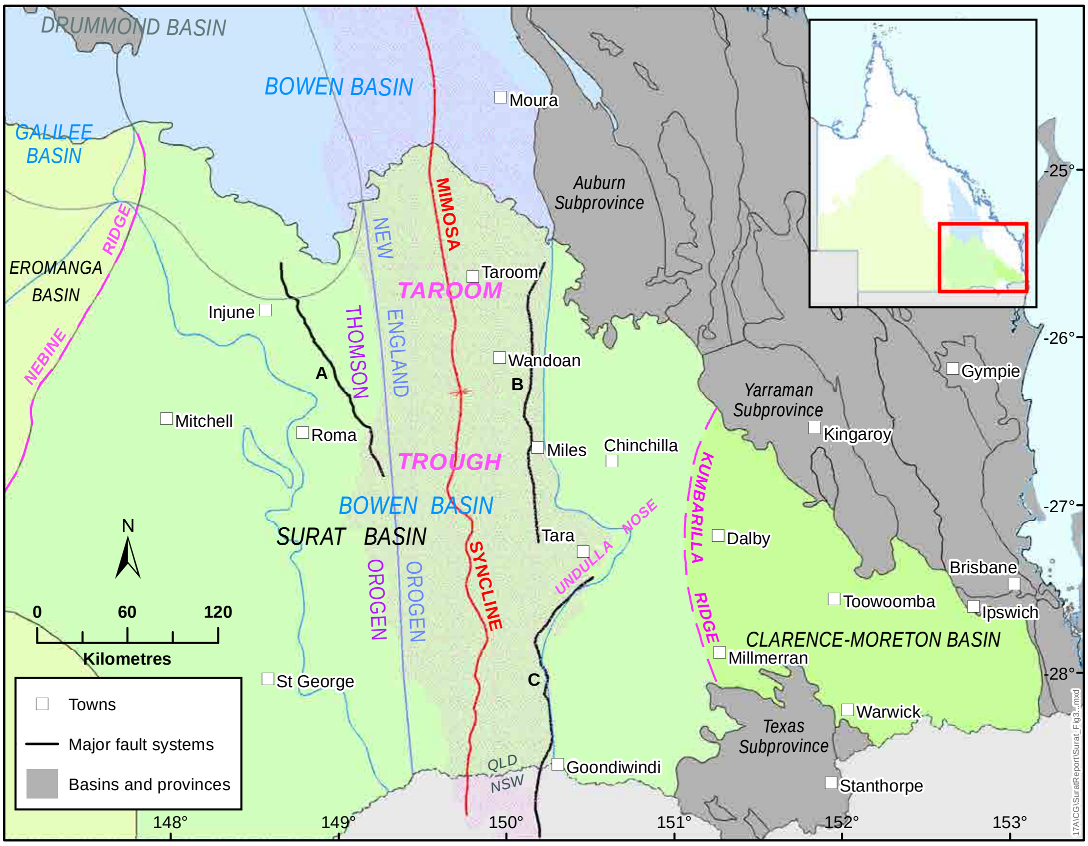


Figure 3. Structural features; A – Hutton-Wallumbilla Fault; B – Burunga-Leichhardt Fault; C – Moonie-Goondiwindi Fault.

The axis of the Mimosa Syncline is roughly meridional in the basin. It plunges to the south possibly along the axis of a parallel fault zone with the eastern deepest part of margin of the Surat Basin against the Devonian to Carboniferous basement rocks and intrusive granites of Permian to Triassic age of the Auburn Province.

The Surat Basin is dominantly weakly deformed with the only minor significant tectonism occurring in the early Late Cretaceous, resulting from the reactivation of Triassic thrust faults in the underlying Bowen Basin (Korsch & others, 2009). This reactivation led to the propagation of some of these faults a short distance up into the Surat Basin, with the magnitude of displacement through the Jurassic strata being poorly constrained but estimated in the range of zero to a few 10s of metres (Hodgkinson & others, 2010a). Some faulting was observed at the top of the Springbok Sandstone at the northwestern margin of the outcrop area on the Chinchilla Sheet area. Current modelling of the 3D seismic over the basin at the University of Queensland (Jeff Copley, personal communication, 2016) should assist in further delineation of major and minor fault features throughout the basin.

More commonly, however, the contraction event caused folding and uplift of the Surat Basin above the reactivated thrust faults (Korsch & others, 2009).

The main structural features in the southern part of the Surat Basin in Queensland are linked to basement features of the Palaeozoic rocks of the New England Province. The Texas Orocline (Texas Sub province) developed as a megafold in the New England Orogen in the Early Permian (Li *et al.*, 2012) and set up a structural regime which appears to have affected the initial deposition and later structural offsets of rocks within the Surat Basin. The megafold is considered to be developed during the Hunter-Bowen Orogeny as is the Leichhardt-Burunga Fault. Movements on these structures apparently occurred during and subsequent to the deposition giving rise to thickness variations in the units of the Surat Basin.

Figure 4 shows interpretation of faulting affecting the basin using the first vertical derivative reduced to the pole magnetics (1vd RTP) in colour ramp. The magnetic image was used to interpret regional fault architecture over the project area and the extent of Cainozoic basalt overlying the target formations. This interpretation of the regional magnetics shows basement structures, and is in addition to the existing structural interpretation of the basin.

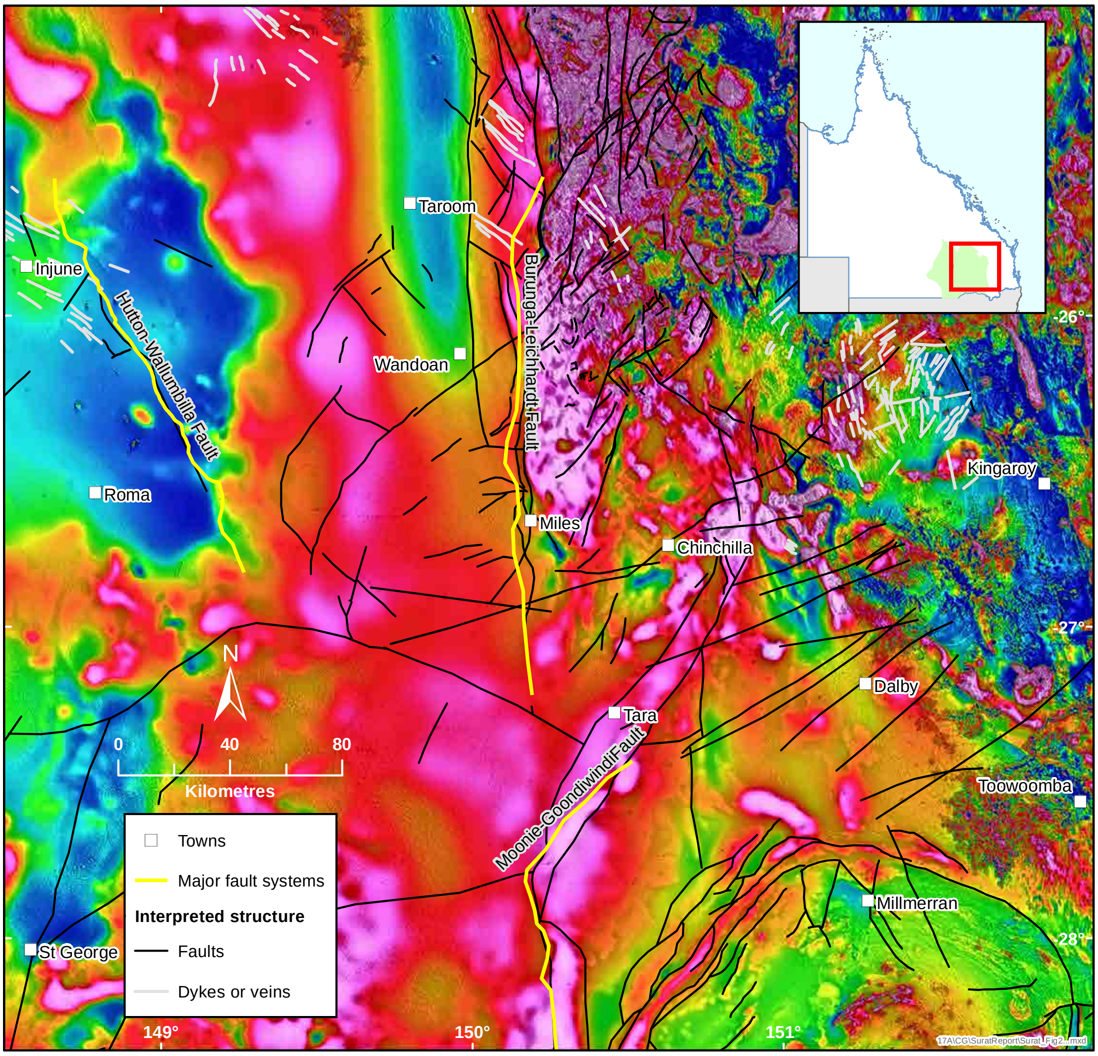


Figure 4. Fault interpretation - 1vd RTP image colour drape.

Normally and reversely polarised magnetic features occurring in the southeastern part of the image in Figure 4 east of Dalby are basalt and trachyte (in some locations) flows from fissure eruptions and local vents that filled valleys of the antecedent streams of the Condamine River.

From an interpretation of the magnetics there are both normally and reversely polarised basalt flows indicating different periods of eruption during the Cainozoic. The 1vd RTP image also shows apparent offsets of basement features through a series of interpreted faults. There are a series of northeast-trending faults in the southeastern part of the image. These faults appear to link to the Moonie–Goondiwindi Fault (Figure 4) and are also evident in thickness variations in the depth to the top of Mesozoic units within the Surat Basin indicating Miocene and or younger movements on these faults. Defining the horizontal and vertical displacement of these faults is beyond the scope of this project.

The northeast-trending structures to the north of the Texas Subprovince appear to control offsets in the subcrop of the Walloon Coal Measures, Springbok Sandstone and Eurombah Formation. Apparent offsets in the boundary of the target units appear to be linked to movements on these basement structures. The interpreted fault network links well with known fault features within the Surat Basin.

Extensive water bore data in the Condamine Irrigation area has been used to model a feature informally termed the ‘Condamine Basin’ herein. Deposits in this basin extend from at least the Palaeocene to the Holocene and contain some basalt flows at depth. The basin sequence is up to 130 m in depth and contains basalt flows more than 88 m thick.

The centre line of the basin is likely to be a fault feature that is roughly parallel to the north-northwest trend of the Main Range Volcanics. The Condamine Basin is filled with alluvial fan and alluvial deposits from different source areas (see Cross Sections) of cover rocks and sediments and is interpreted as a late Cainozoic extensional basin.

The contours presented in Figure 5 were produced using data from more than 4000 water bores (Leon Leach, personal communication, 2016). It is notable that the extension of faults to the west also links to offsets in the isopachs in the Walloon Coal Measures and these are visible in offsets of magnetic basement to the east (Figure 4). Methane seeps within the Condamine River seem to have occurred in an alluvial depocentre and along a fault line.

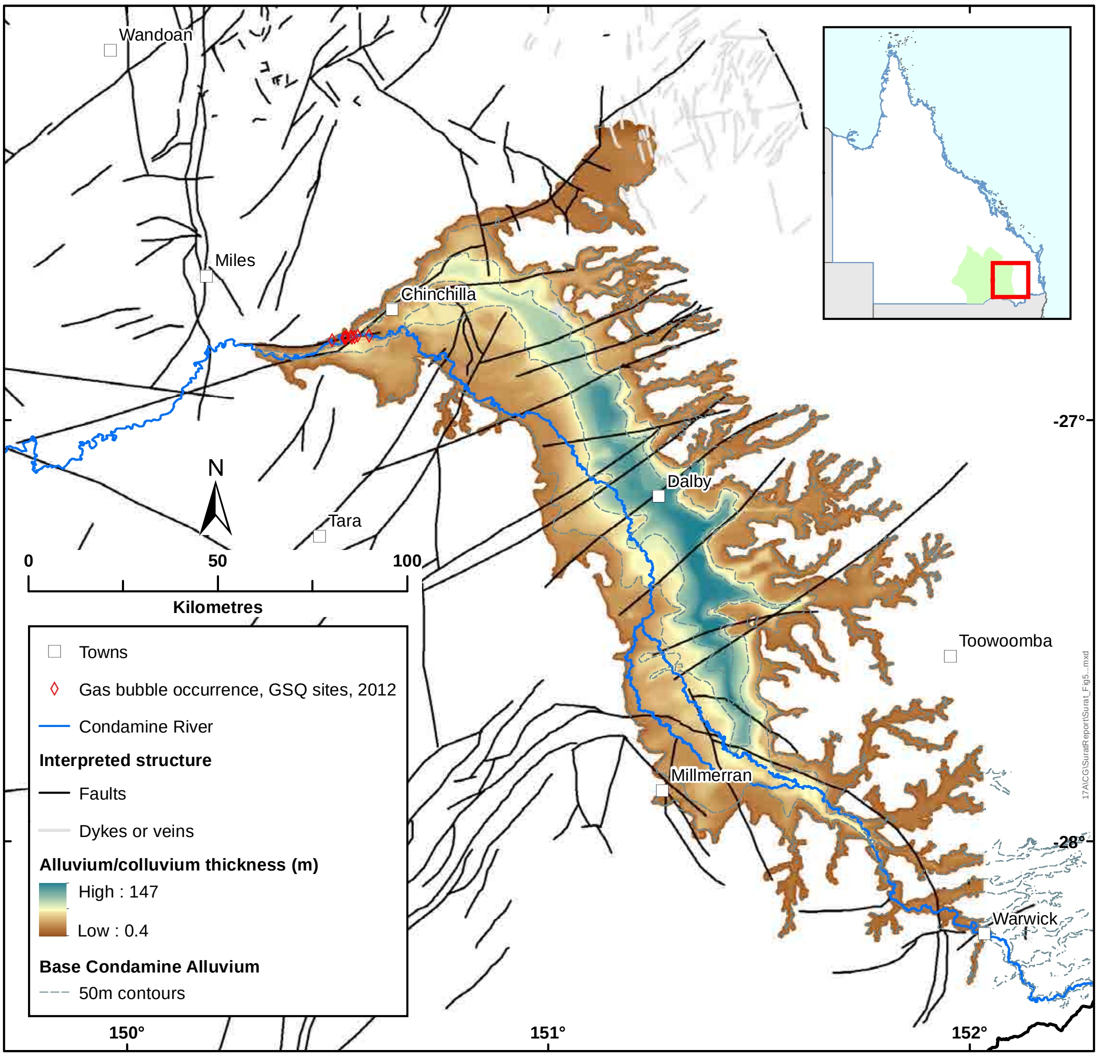


Figure 5. Interpreted basement faults and their relation to the thickness of the Condamine Alluvium.

Cainozoic landscapes and cover

Laterite profiles developed on rocks in the Chinchilla and Dalby 1:250 000 Map Sheets in the transitional zone between the Clarence–Moreton and Surat Basins led Exon *et al.* (1968) to define a unit named 'Kumbarilla beds'.

The Kumbarilla beds comprise both lateritised and weakly weathered units. They represent deeply weathered parts of the Springbok Sandstone, Westbourne and Orallo formations and the Gubberamunda Sandstone. The lowest part of the Kumbarilla beds was interpreted as the Springbok Sandstone, but its extent was not defined.

A regional view of the deep weathering profile over the project area reveals that the most significant area of deep weathering is present to the south of the outcrop area on the Roma and Taroom 1:250 000 Map Sheet areas, to the east of the major northerly trending Burunga-Leichhardt Fault zone on the Chinchilla and Dalby 1:250 000 Map Sheet areas.

This suggests a post-lateritic (? Post – Pliocene) movement with a relative west-block-up reverse sense of movement accompanied by an upward tilting to the north. Deep weathering profiles are commonly stripped off different geological units in the northern Roma and Taroom 1:250 000 Map Sheet areas, but not on the southeastern side of the fault. This displacement may be very small (only 10–20 m) as there are laterite remnants in the outcrop areas.

The thicknesses of the sediment and the occurrence of Cainozoic basalt in the Condamine Basin indicates that there is considerable faulting and infilling of the basin with alluvial and colluvial deposits and basalt (in some locations).

It appears that the cover including the alluvium and colluvium plus the basalt locally exceeds 130 m in thickness.

The actual subsurface extent of basalt under alluvial and colluvium is difficult to determine. The water bore logs are inconsistent in their logging and the magnetic 1vd RTP image shows there are magnetic features related to basalt detritus (possibly including maghemite) below the Condamine Basin around Dalby (Figure 4). These features are indistinct on the magnetic images (1vd, 2vd and analytical signal). Because of this, the extent of older basalt flows beneath the alluvial and colluvial sediments of the Condamine Basin is uncertain.

The blurred nature of the magnetic signal suggests the transported alluvium and colluvium may contain basaltic rock fragments that have a residual magnetism. The resolution of the magnetic data is insufficient to identify the extent of the basalt in the basin so this has not been interpreted.

Basalt of the Main Range Volcanics flowed to the east and west during the Oligocene to Miocene from about 30 to 20 Ma. Concurrently to the west, it appears the Condamine Basin was subsiding along a northwesterly-trending fault structure with basalt flows filling sections of the deepest parts of the basin (e.g., water bore RN 83741 (Latitude 27.602778°S; Longitude 151.752222°E) which bottomed in basalt at 88 m). The basin appears to represent a half graben structure with a syn-rift fill. Deeply weathered (Canaway profile Oligocene–Miocene) sediments in the vicinity of the Chinchilla Weir (Figure 18) may represent the earliest fill of the Condamine Basin, implying that it is older than the Main Range Volcanics.

There is little evidence that basalt filled the majority of the basin. The basalt units in water bores in the eastern part of the basin possibly contain significant amounts of basalt detritus shed from developing alluvial fan materials. In addition, the radiometric signature of surficial sediments (Figure 4) assisted the mapping of basalt extent. The basalt and the associated sediments contain high potassium (red areas in Figure 6). The locations of water bores with stratigraphic logs that report basalt from Main Range Volcanics and the associated basalt-derived sediments are shown in Figure 7.

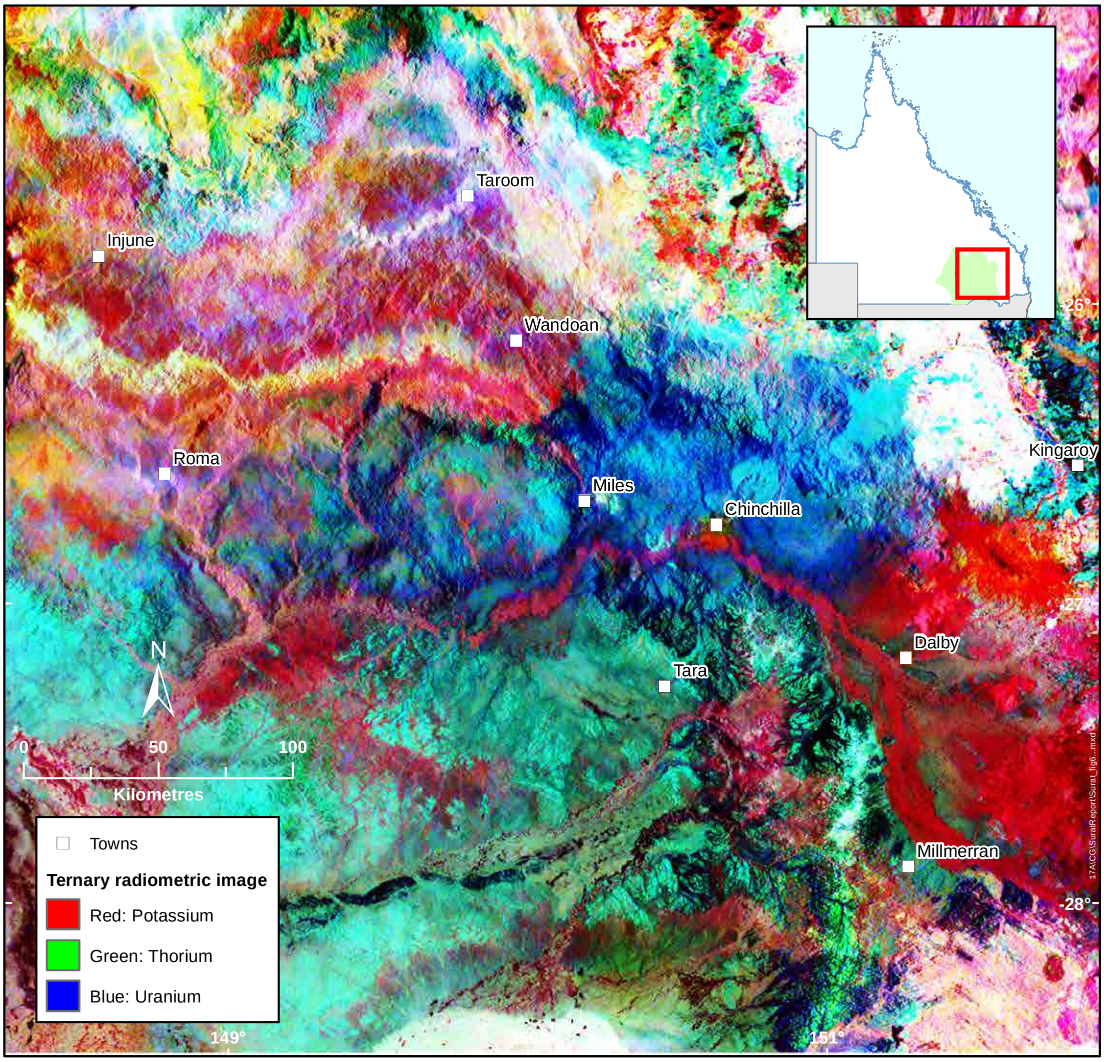


Figure 6. Radiometric ternary image of project area; high potassium content (red colouration) is associated with basalt occurrence; high thorium content is coloured green; high uranium content is coloured blue.

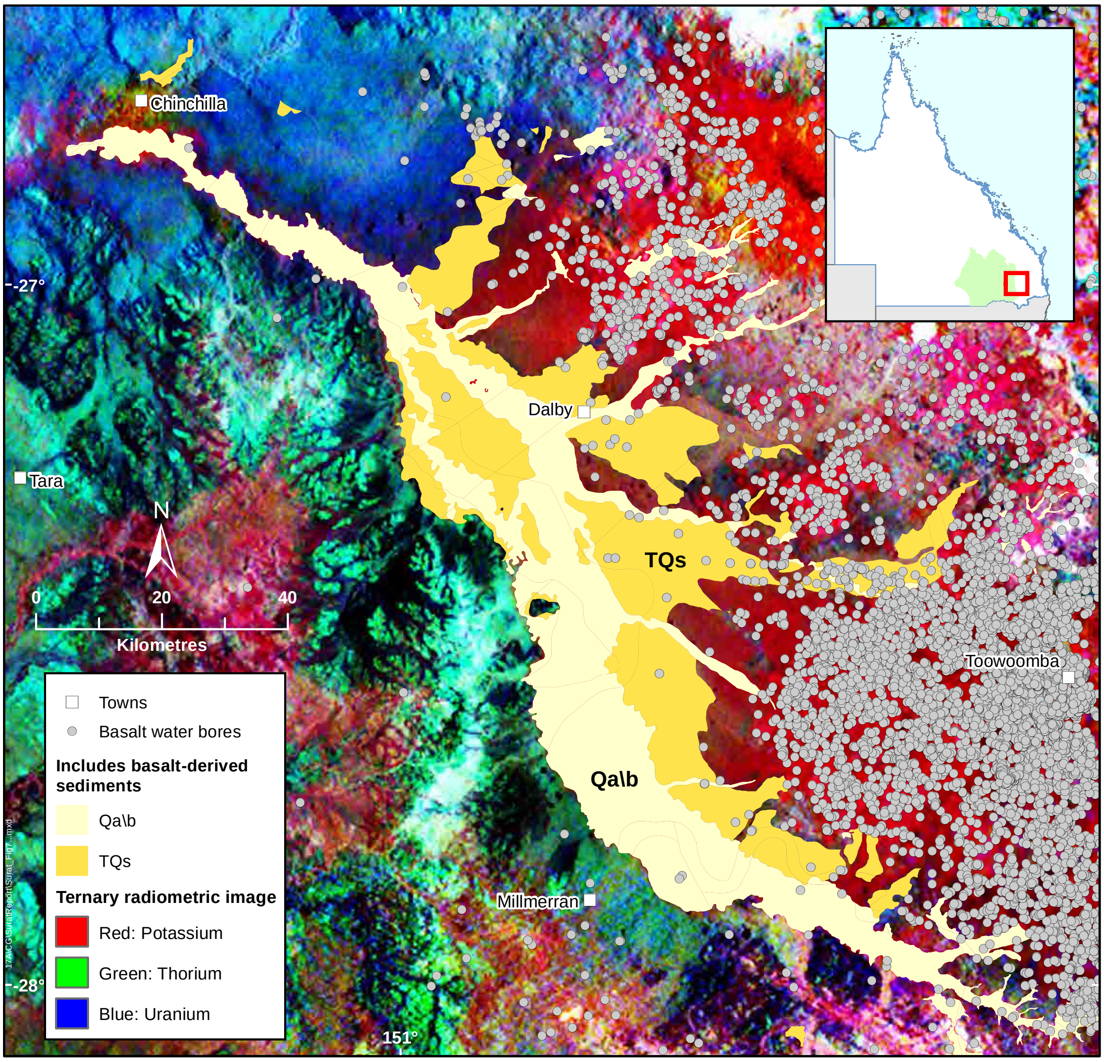


Figure 7. Water bores with stratigraphic logs that report basalt and new colluvium boundaries in the Condamine Basin.

Linking XRF data to radiometric data

Initially a series of point data from the radiometric image values were sampled from the target formations in the outcrop area. These points from the digital radiometric data show differences between the formations as mapped.

A field program was undertaken from 23-27 November 2015 to investigate the units overlying and underlying the Walloon Coal Measures and Springbok Sandstone, and to define the top of the succession of interest. Samples of rock units collected during this trip (Boxvale Sandstone Member of the Evergreen Formation, Hutton Sandstone, Walloon Coal Measures, Springbok Sandstone, Westbourne Formation and Gubberamunda Sandstone) were subjected to hand-held XRF analysis. In addition to these samples, the Niton XRF analyser was used to examine formations of interest in core from stratigraphic bores showing key type sections in GSQ DRD 26, GSQ Roma 4 and GSQ Roma 7.

A summary of the apparent lithological and geophysical characteristics of these units and outcrop pattern characteristics are provided below. The values on the potassium (K) vs thorium (Th) plot were generated from individual channels as spot values from the formations as originally mapped from the radiometric imagery.

Figure 8 shows the previous geological boundaries in relation to sites which were tested for their radiometric signature (Appendix 7). The Boxvale Sandstone Member was previously only mapped west of the Mimosa Syncline but it has now been extended eastwards based on radiometric signatures and field measurements. The Hutton Sandstone was subdivided into lower and upper Hutton. The Injune Creek Group was divided into its components: the Walloon Coal Measures and Springbok Sandstone. The Westbourne Formation was initially mapped only in the west, north of Roma and now extended east, towards Wandoan.

Figure 9 displays two black correlation lines drawn through points originally mapped as Walloon Coal Measures. A reinterpretation of the area using borehole information and additional interpretation of the radiometrics of the zone above the top of the Hutton Sandstone showed that some of the original W dots with higher Th values could now be attributed as Eurombah Formation.

Walloon Coal Measures, Eurombah Formation and Springbok Sandstone have relatively similar K and Th values. Lithologically, the Springbok Sandstone appears higher in feldspar than the bulk of the Walloon Coal Measures and it has well developed stacked trough cross bedding (although in outcrop on the Undulla Nose it contains planar cross bedding) compared with the Walloon Coal Measures that are characterised in outcrop by laminar, thin to very thin sandstone units that have only rare cross bedding.

There is an area previously mapped as Walloon Coal Measures on the western part of the Taroom Sheet that had higher K and Th values than the bulk of the Walloon Coal Measures. This upper zone of higher Th is now recognised as outcrop of Eurombah Formation (Figure 9) and occurs adjacent to the Eurombah Dome. This formation was recognised and mapped as a separate unit on the Roma 1:250 000 Map Sheet (Milligan & Exon, 1967) but was not mapped on the adjacent Taroom Sheet to the north (Forbes *et al.*, 1967), creating an anomaly across the map sheet boundaries.

The Westbourne Formation has similar K values to the other units (particularly the Hutton Sandstone) but is distinguished by its significantly higher Th (over 10 ppm) from the underlying Springbok Sandstone. The Westbourne Formation is poorly exposed and only one sample was collected from a creek exposure during field investigations for analysis. It is generally best exposed in watercourses. A good example of the Westbourne Formation outcrop can be found at Pine Hills Station north of Wallumbilla and significant surface exposure can be found on Norwood Station north of Yuleba (Peter Evans, personal communication, 2016). On Figure 9, most values from the Westbourne Formation (Ws) contained greater than 10 ppm Th.

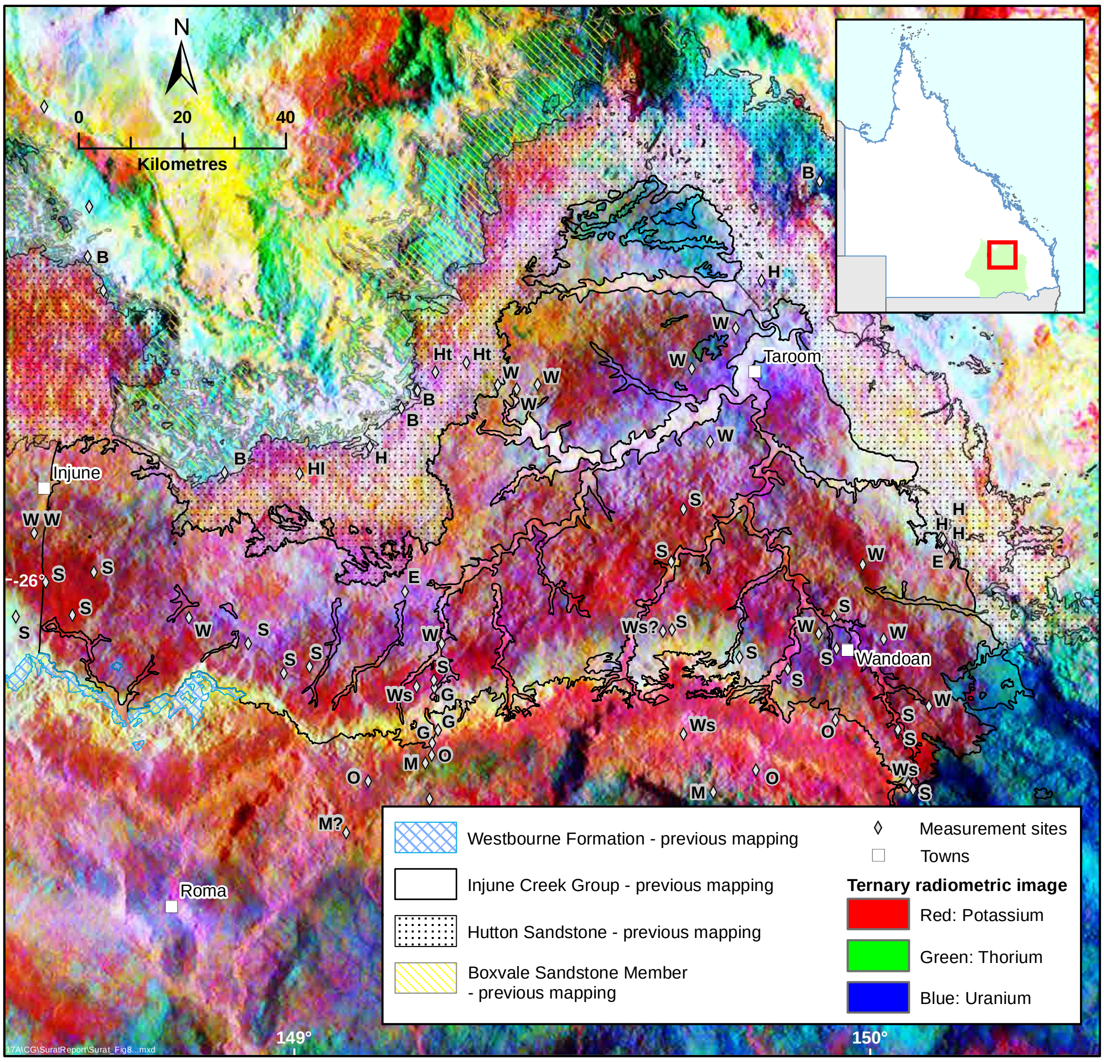


Figure 8. Field measurements sites in relation to previously mapped geological boundaries. B – Boxvale Sandstone Member, Hl – lower Hutton Sandstone, Ht – upper Hutton Sandstone, H – undifferentiated Hutton Sandstone, E – Eurombah Formation, W – Walloon Coal Measures, S – Springbok Sandstone, Ws – Westbourne Formation, G – Gubberamunda Sandstone, O – Orallo Formation, M – Mooga Sandstone.

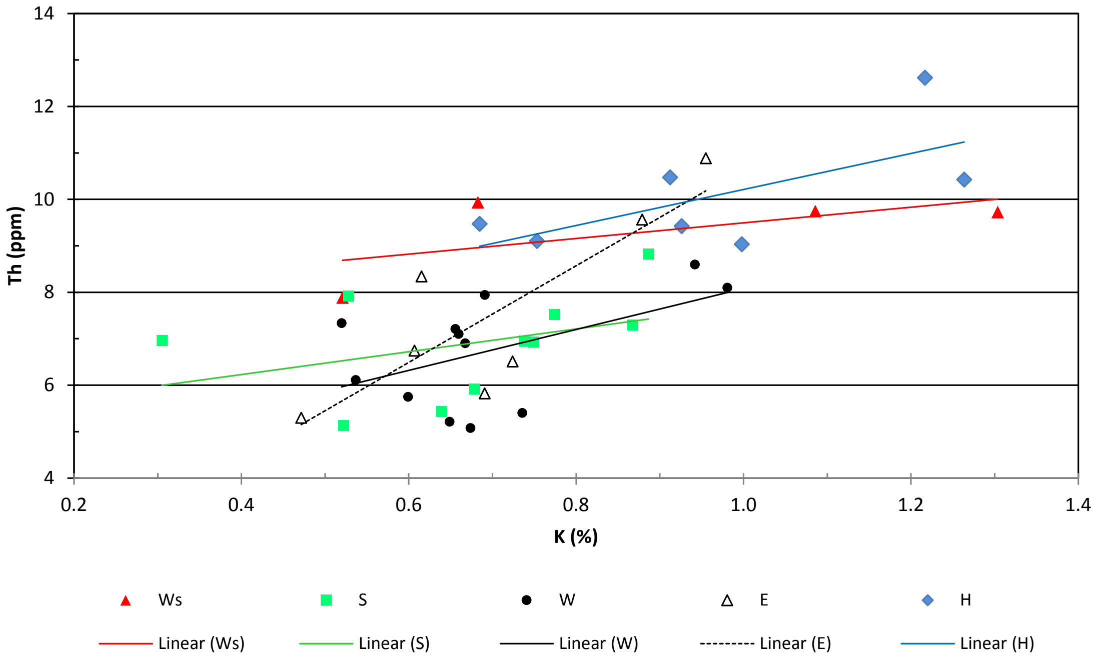


Figure 9. K vs Th for formations: Ws – Westbourne Formation, S – Springbok Sandstone, W – Walloon Coal Measures, E – Eurombah Formation and H – Hutton Sandstone.

In contrast to the Westbourne Formation, the Gubberamunda Sandstone is a thick bedded to massive quartz-rich unit in outcrop. Samples were tested from outcrop and subsurface core to compare with the underlying Westbourne Formation. The Gubberamunda Sandstone contains almost no feldspar and is low in K and Th.

The Orallo Formation is a distinctly different unit to the others examined with K values greater than 1%, Th greater than 5 ppm and low uranium (U), generally less than 1 ppm.

The Mooga Sandstone has a generally higher radiometric response than the underlying Orallo Formation and was sampled on the field trip.

The Hutton Sandstone has high K and Th values explaining its bright values on the ternary image.

In general, in outcrop, the Gubberamunda Sandstone is porous and ferruginised quartz-rich sandstone, which forms a major regional aquifer. The Gubberamunda Sandstone locally has the lowest K and Th levels on the K vs Th plot, but its responses are variable. The plots of Walloon Coal Measures and Springbok Sandstone are generally similar to those generated from the radiometric image plot (Figure 6), while the Westbourne Formation has typically higher Th values in borehole GSQ Roma 4. Each of the formations fell generally into specific correlation regions on the Th vs K*10 region; note the compositional differences between outcrop and core samples for the same formation (Figure 10).

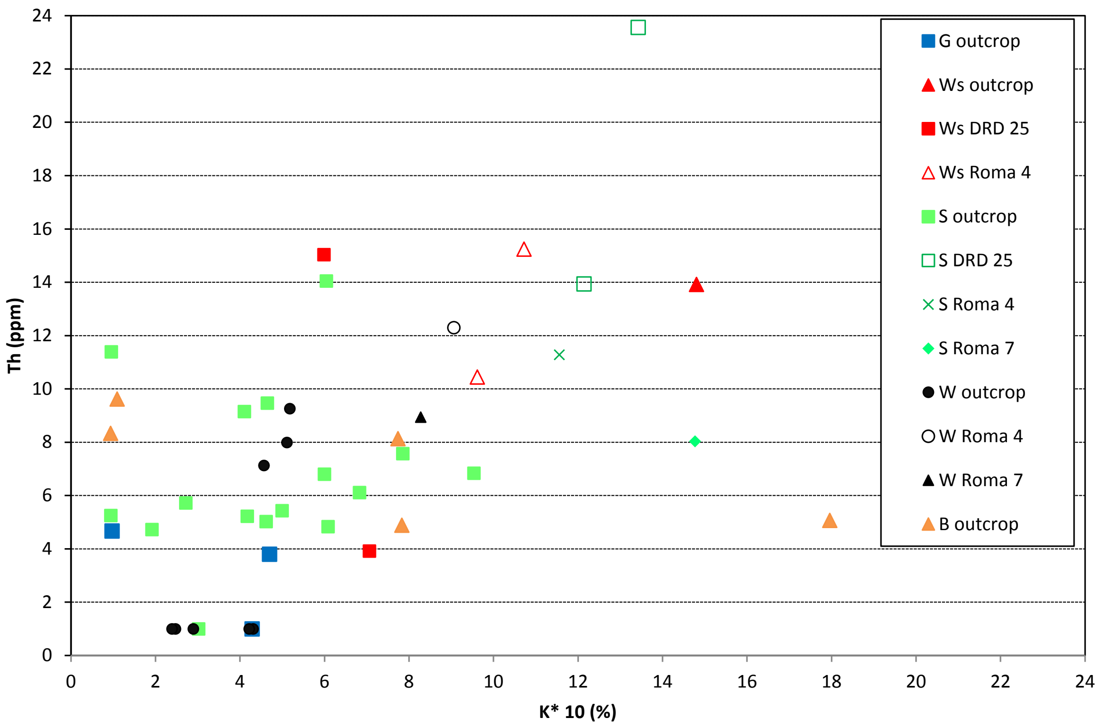


Figure 10. Niton XRF results from outcrop and core from GSQ DRD 25, Roma 4 and Roma 7: G – Gubberamunda Sandstone; Ws – Westbourne Formation; S – Springbok Sandstone; W – Walloon Coal Measures B – Boxvale Sandstone Member.

Defining the target units

An assessment of the stratigraphic sequence from the base of the Eurombah Formation through the Walloon Coal Measures to the top of the Springbok Sandstone required the specific definition of the units above and below these target units. In particular consideration was given to the Hutton Sandstone – Evergreen Formation succession, the units of the Marburg Subgroup that underlie the Eurombah Formation and the Westbourne Formation that overlies the Springbok Sandstone.

The creation of a new geological map of these units from a desktop study needs a number of absolute criteria or 'anchor points' to uniquely define geological units that are universally agreed.

The change at the top of the Hutton Sandstone / Marburg Subgroup into the transitional rock types of the lowest coal seams of the Walloon Coal Measures is one of these anchor points. This anchor point is defined radiometrically using both the ternary radiometric image and the thorium channel. In the outcrop area of the Taroom 1:250 000 Map Sheet, the Hutton Sandstone has high K and Th levels compared with the lower radiometric response of the Eurombah Formation and Walloon Coal Measures (Figure 11).

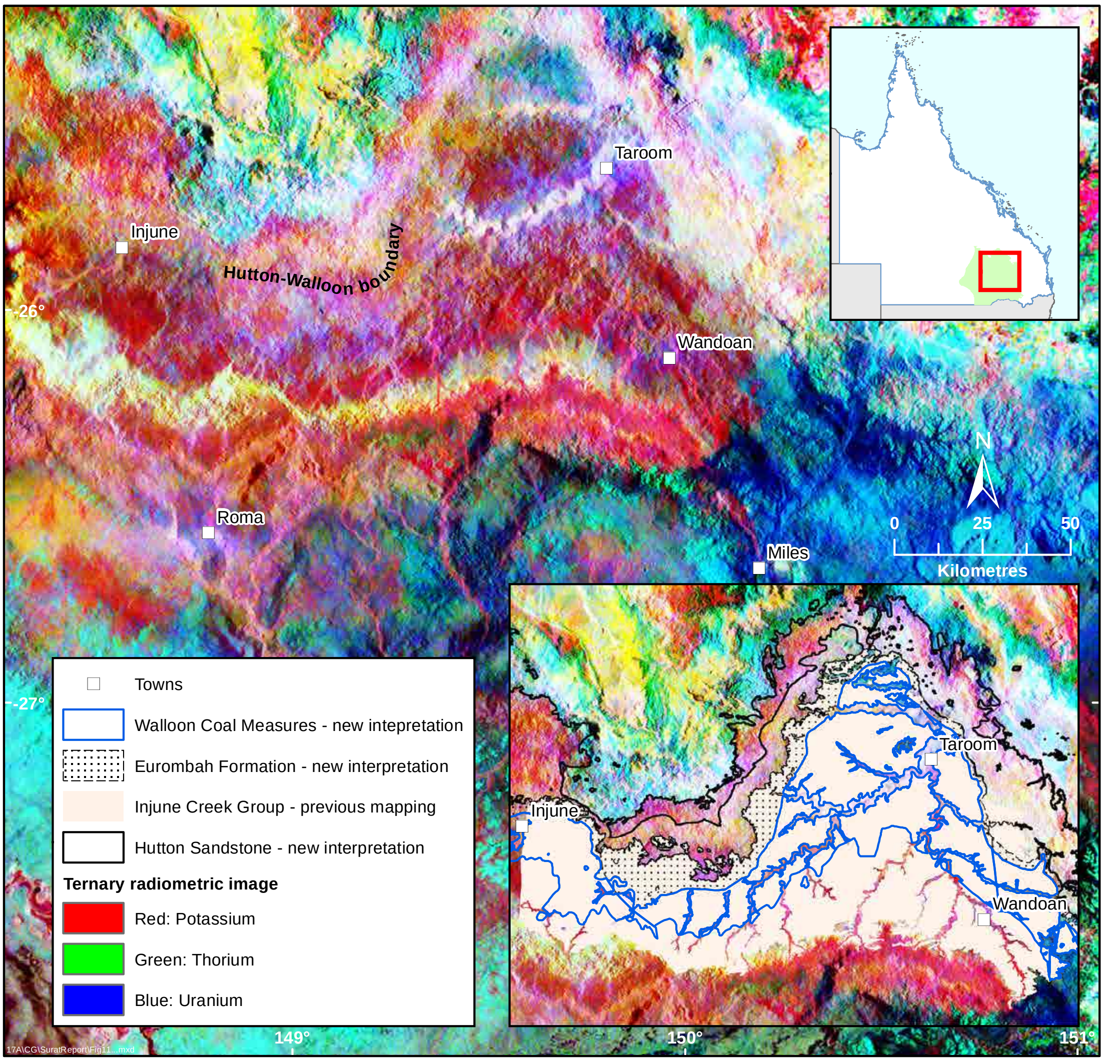


Figure 11. Hutton Sandstone – Walloon Coal Measures (including Eurombah Formation) geological boundary and radiometric signatures.

On the western limb of the Mimosa Syncline is the Eurombah Dome and the Eurombah Formation defined by Milligan & Exon (1967). In this area (Taroom Sheet), there are outliers mapped as Walloon Coal Measures which overlie the upper part of the Hutton Sandstone (Forbes *et al.*, 1967). These outliers are likely to be Eurombah Formation which have a radiometric signature influenced by slope wash at the basin margins that mask the radiometric signature of the upper part of the Hutton Sandstone that outcrops in the area. However, logs from CSG wells have established that this region is dominantly Hutton Sandstone, and that the original mapped boundary of the top of the Hutton Sandstone north of the Eurombah Dome is essentially correct.

The next anchor points in this process are those that uniquely define the coal seam gas producing units (herein the Walloon Coal Measures) and the consolidated and unconsolidated units that overlie them.

In this project the base of the Walloon Coal Measures is defined by the lowermost persistent coal seam and this is discussed further in the section on Walloon Coal Measures.

The Springbok Sandstone that forms the top coal seam gas producing unit unconformably overlies the Walloon Coal Measures. The unconformity, as defined in studies by OGIA in boreholes as the depth to 'SPUNCON', is a well-recognised intersection in boreholes and forms a fundamental anchor point. The unconformity cuts into the top coals of the Walloon Coal Measures (Juandah Coal Measures) and to assist in defining this unconformity, intersections less than 100 m to SPUNCON in water and coal seam gas and coal exploration drilling data were used. These intersections were also linked to the occurrence of coal mines and coal resources at the top of the Walloon Coal Measures in an attempt to delineate the boundary between these units.

In addition, local knowledge of the occurrence of a persistent sandstone roof to the upper coal seams of the Walloon Coal Measures in mines formed another piece of evidence to define the 'SPUNCON' unconformity which forms the base of the Springbok Sandstone / top of the Walloon Coal Measures. The base of the Springbok Sandstone appears to be defined by a higher K level coupled with a subtle change in elevation which can be discerned on the DEM image linked to the ternary radiometric image in the outcrop area (Figure 12).

In the outcrop area (not covered by laterite) in the Roma and Taroom 1:250 000 Map Sheets, the top of the Springbok Sandstone (base of Westbourne Formation) was a radiometric anomaly defined by a higher Th radiometric response on the ternary radiometric image. This anomaly is both a K and Th high, but shows best in the Th channel image and it is distinguished as a pale yellow colour on the ternary (K-Th-U ternary image, Figure 13)..

In the subcrop regions, the top of the Springbok Sandstone was defined by extrapolation between the top of the Springbok being less than 100 m below surface and using the observation that the overlying Westbourne Formation is finer grained and has a more subdued topography. Determining the base of the Springbok Sandstone in the subcrop required use of a combination of the water bores and CSG wells to initially define a depth of less than 100 m to SPUNCON which was then combined with the topographic difference from the upper coals of the Walloon Coal Measures to the more resistant base of the Springbok Sandstone. In addition, coal resource polygons and local knowledge were applied to identify the sandstone roof to the coals of the uppermost Walloon Coal Measures. This was refined using specific CSG well data which improved the accuracy of the interpretation.

As there is significant deep weathering south of the Taroom Map Sheet area, the rock chemistry differences between the constituent units is not recognisable. On the ternary radiometric image, almost all units have a greenish tinge caused by high Th. The interpretation for this is that the most resistant mineral in the landscape is zircon and, as this mineral contains Th, the Th anomaly that characterises the base of the Westbourne Formation in the outcrop area thus could not be used to determine the top of the Springbok Sandstone in this area. In addition, this region also contains a blanket of Cainozoic sediments, sedimentary rocks and basalt that needed to be interpreted from borehole information.

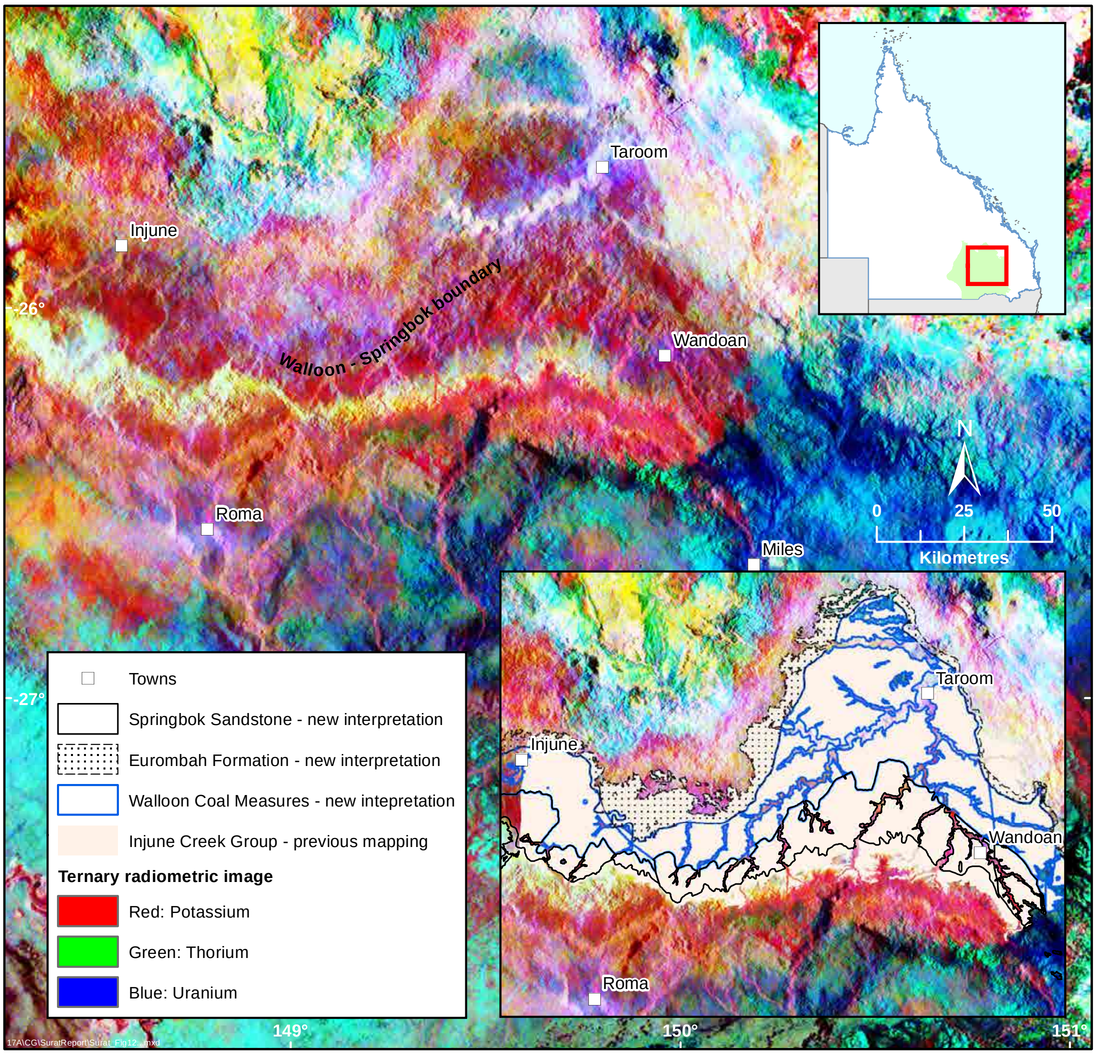


Figure 12. Walloon Coal Measures – Springbok Sandstone geological boundary and radiometric signatures.

The most difficult boundary to define was the basal boundary of the Walloon Coal Measures. In the past, mapping in the Roma 1:250 000 Map Sheet (Milligan & Exon, 1967) defined the Eurombah Formation between the top of the Hutton Sandstone and the base of the Walloon Coal Measures in the vicinity of the Eurombah Dome to the west of the Mimosa Syncline. This unit was not recognised during the regional mapping of the Taroom 1:250 000 Sheet area (Forbes *et al.*, 1967), but was defined in borehole data and the likely extent was mapped as part of this phase of the project. The thickness of this unit is variable and its lateral extent has been estimated in regions of poor exposure from subtle changes in radiometric signatures compared with the overlying Walloon Coal Measures.

Additional units have been defined between the top of the Hutton Sandstone / Marburg Subgroup and the base of the Walloon Coal Measures which some authors have defined as one or two additional units. Accordingly, to date, the base of the Walloon Coal Measures has not been well defined. Table 1 summarises the approach by previous authors and the logic followed in this report.

The base of the Walloon Coal Measures is defined, in this report, as the first significant coal intersection. This definition is in line with economic and practical considerations and allows the consolidation of the mapping of transitional units between the top of the Hutton Sandstone / Marburg Subgroup and the economic coal seams of the Walloon Coal Measures into a single entity, the Eurombah Formation.

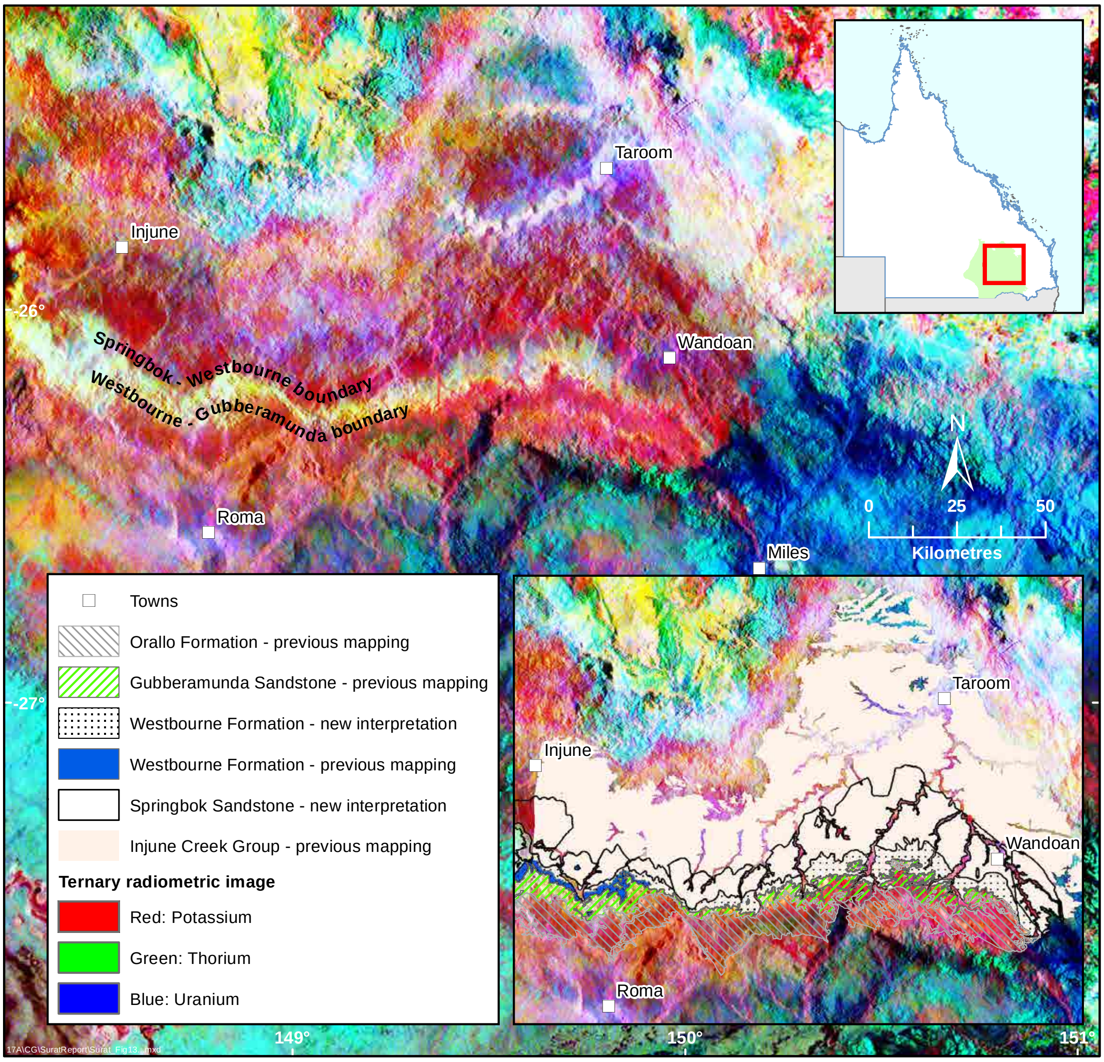


Figure 13. Westbourne Formation geological boundaries with the Springbok Sandstone and younger formations, and their radiometric signatures.

Table 1. Correlation of the Walloon Coal Measures.

Swarbrick, 1973		Scott *et al.*, 2004		Ryan *et al.*, 2012 (QGC) & this report	
Springbok Sandstone	Unit 9	Springbok Sandstone	Unit 9	Springbok Sandstone	Unit 9
Walloon Coal Measures	Unit 8	Walloon Coal Measures	Unit 8	Walloon Coal Measures	Unit 8
	Unit 7		Unit 7		Unit 7
	Unit 6		Unit 6		Unit 6
	Unit 5		Unit 5		Unit 5
	Unit 4	Durabilla Formation	Unit 4		Unit 4
	Unit 3		Unit 3		Unit 3
Eurombah Formation	Unit 2	Eurombah Formation	Unit 2	Eurombah Formation	Unit 2
	Unit 1		Unit 1		Unit 1
Hutton Sandstone		Hutton Sandstone		Hutton Sandstone	

The Eurombah Formation has bed forms similar to the underlying Hutton Sandstone / Marburg Subgroup, with sandstone compositions of lithic labile which are transitional between the Walloon Coal Measures and the Hutton Sandstone, whereas the Durabilla Formation (informal status according to the Australian Stratigraphic Units Database) is apparently compositionally more similar to the Walloon Coal Measures and has similar bed forms. The base of the Walloon Coal Measures is herein defined as occurring at the base of the Taroom Coal Measures which Scott (2008) states is uniquely defined by the gamma, density and resistivity wireline logs from the underlying Durabilla Formation. However, on the available log data (Appendix 4), it is not possible to split the transitional unit between the top of the Hutton Sandstone / top of Marburg Subgroup and the base of the Walloon Coal Measures; consequently, both lower and upper transitional units have been included in the Eurombah Formation.

In the determination of this boundary, borehole intersections, coal resource polygons, radiometrics and the DEM were used in different areas to best define the boundary.

The distribution of the Mesozoic units is indicated in Appendices 1 and 2 which, respectively, provide a surface geological map and a geological map with the cover sequences removed, both at 1: 500 000 scale. The cross sections (see chapter Cross Sections) illustrate the current knowledge of the relationship between the cover sequences and the underlying Mesozoic geology and between the constituent Mesozoic units.

The above units are described in more detail below.

Stratigraphic descriptions

Evergreen Formation

Nomenclature

Jensen *et al.* (1964) defined the Evergreen Formation to include the "Evergreen Shales" of Whitehouse (1944). The term Evergreen Shales was originally attributed to the shaly unit between the Precipice Sandstone and the Boxvale Sandstone of Reeves (1947) in the valley of the Dawson River. Jensen *et al.* (1964) included the Boxvale Sandstone as a member of the Evergreen Formation which contained an upper shaly member with an oolitic ironstone at its base. The upper shaly unit was upgraded to member status as the Westgrove Ironstone Member on the western margin of the Mimosa Syncline by Mollan *et al.* (1965). An equivalent unit, that has not been formally defined (Green *et al.*, 1997), also occurs on the eastern side of the Mimosa Syncline. It is shown as Je2 on the accompanying map (Appendix 1) north of Injune as an upper mudstone, siltstone and sandstone containing an oolitic basal member (now Westgrove Ironstone Member).

Lithology

The Evergreen Formation below the Boxvale Sandstone Member comprises green-grey, labile and sublabile, fine- to medium-grained sandstone, carbonaceous mudstone and argillite and minor carbonaceous siltstone, shale and coal. It appears to be, in part, a correlative of the Gatton Sandstone at the base of the Marburg Subgroup in the Clarence–Moreton Basin.

The Boxvale Sandstone Member commonly comprises thinly to thickly bedded, fine- to coarse-grained, cross-bedded, quartzose sandstone, with some argillaceous clay matrix. It is apparently not present in the Clarence–Moreton Basin. On the western and northeastern limbs of the Mimosa Syncline, as confirmed during field mapping in November 2015, the Boxvale Sandstone Member forms a thick-bedded to massive quartzose sandstone. Intervals of thinly bedded, very fine grained, porous quartzose sandstone with carbonaceous siltstone, shale and coal interbeds are also present in boreholes, but were not observed during the November 2015 field program.

The upper Evergreen Formation (including Je2), between the Boxvale Sandstone Member and the base of the Hutton Sandstone, comprises mainly dark grey to black mudstone, laminated with sandstone, siltstone and shale and fine-grained, sublabile to labile sandstone (Green *et al.*, 1997). The Westgrove Ironstone Member forms the lower part of this interval and comprises interbedded mudstone and chamositic mudstone with a pelletal or oolitic structure and sideritic cement, and minor labile sandstone.

Over much of the area the Evergreen Formation has a basal sandy interval characterised by mainly sublabile sandstones. In the past this interval commonly has been placed in the upper part of the Precipice Sandstone.

Grigorescu (2011) described the mineralogy of the Evergreen Formation of the northeastern Surat Basin in Queensland, and showed that the formation represented a lower aquitard seal for the Hutton Sandstone. The environment of deposition of the Evergreen Formation represents a change from braided to meandering fluvial systems. Twenty-nine samples of this unit were analysed by XRD and optical microscopy for Grigorescu's study. Quartz is the main component (25–97%) and kaolinite (2–35%) is the dominant clay mineral. Mixed-layer clays vary from smectite-rich to illite-rich. Farquar *et al.* (2013) described the mineralogical characteristics of the unit arguing its potential as a reservoir system for CO_2 sequestration.

Thickness

In the project area the Evergreen Formation is up to 307 m thick; however, its thickness more commonly ranges from 0 to 250 m (Green *et al.*, 1997). The current maximum thickness of the unit is 451.4 m in OEC Spring Gully (drilled in 2006) but a more representative thickness is 264.4 m from SSL Fairview 214 drilled in 2009 (QPED database, 2015).

Relationships

The Evergreen Formation conformably overlies the Precipice Sandstone and is conformably overlain by Hutton Sandstone. The unit unconformably overlies Nogo beds, Narayen beds, and Torsdale Volcanics on the Mundubbera 1:250 000 Map Sheet area. It is laterally continuous with the lower part of the Marburg Subgroup, Clarence–Moreton Basin and is correlated with the Ma Ma Creek Member of the Koukandowie Formation and the Gatton Sandstone.

Age

The age of the Evergreen Formation is based on palynofloras identified as being of Pliensbachian–Toarcian in age, associated with palynological units APJ2.2, APJ3.1, and lowermost APJ3.3 (Green *et al.*, 1997; Price, 1997; McKellar, 1998; and Jell 2013, figure 7.2. Spinose acritarchs and leiospheres are common to abundant in palynofloral assemblages from the Boxvale Sandstone and Westgrove Ironstone members, (Evans, 1966; Paten, 1967; Reiser & Williams, 1969; McKellar, 1974, 1998), but there are no definite fossil indicators of a marine environment.

Depositional setting

The Evergreen Formation below the Boxvale Sandstone Member is interpreted to have been deposited in freshwater lakes (Mollan *et al.*, 1972) or by meandering streams in coastal plains and in deltas (Exon, 1976). Fielding (1989) interpreted that the upper part of the Boxvale Sandstone Member was deposited as part of a prograding lacustrine delta system. Exon (1976) concluded that during deposition of the Boxvale Sandstone Member, the Surat Basin consisted of a series of small lakes fed by fluvial systems with associated deltas.

The Boxvale Sandstone Member has not been recognised in all wells and is commonly absent in those near the limit of deposition of the Evergreen Formation (Green *et al.*, 1997). This restriction is most likely due to a limitation of the 'Evergreen lake systems' which formed towards the centre of the basin. Fluvial systems flowing into the lakes derived from a quartz-rich source (possibly granites of the Auburn Arch?) providing a source of sediments for the Boxvale Sandstone, would have occurred near the edges of the basin. The Boxvale Sandstone was identified on the eastern limb of the Mimosa Syncline through a greenish radiometric signature which mimicked the pattern on the western limb of the Mimosa Syncline (Figure 14).

An exposure of the Boxvale Sandstone to the northeast of the Hutton Sandstone is shown in Plate 1.

Mollan *et al.* (1972) interpreted that the Westgrove Ironstone Member was deposited under shallow marine conditions based mainly on the presence of the ironstone oolites. Cranfield *et al.* (1994) have shown that the ironstone oolites in the Surat, Clarence–Moreton, Nambour and Maryborough Basins were deposited in a lake environment. Bradshaw & Yeung (1990, 1992) and Bradshaw & Challinor (1992) associated a paralic environment with the ironstone oolite facies. They suggested that the rise of sea level to a peak in the mid Toarcian caused the inflow of brackish water into the lacustrine (lagoonal) systems of eastern Australia, but the contribution of freshwater from the surrounding hinterland of rivers, lakes and coal swamps prevented marine conditions from fully developing.

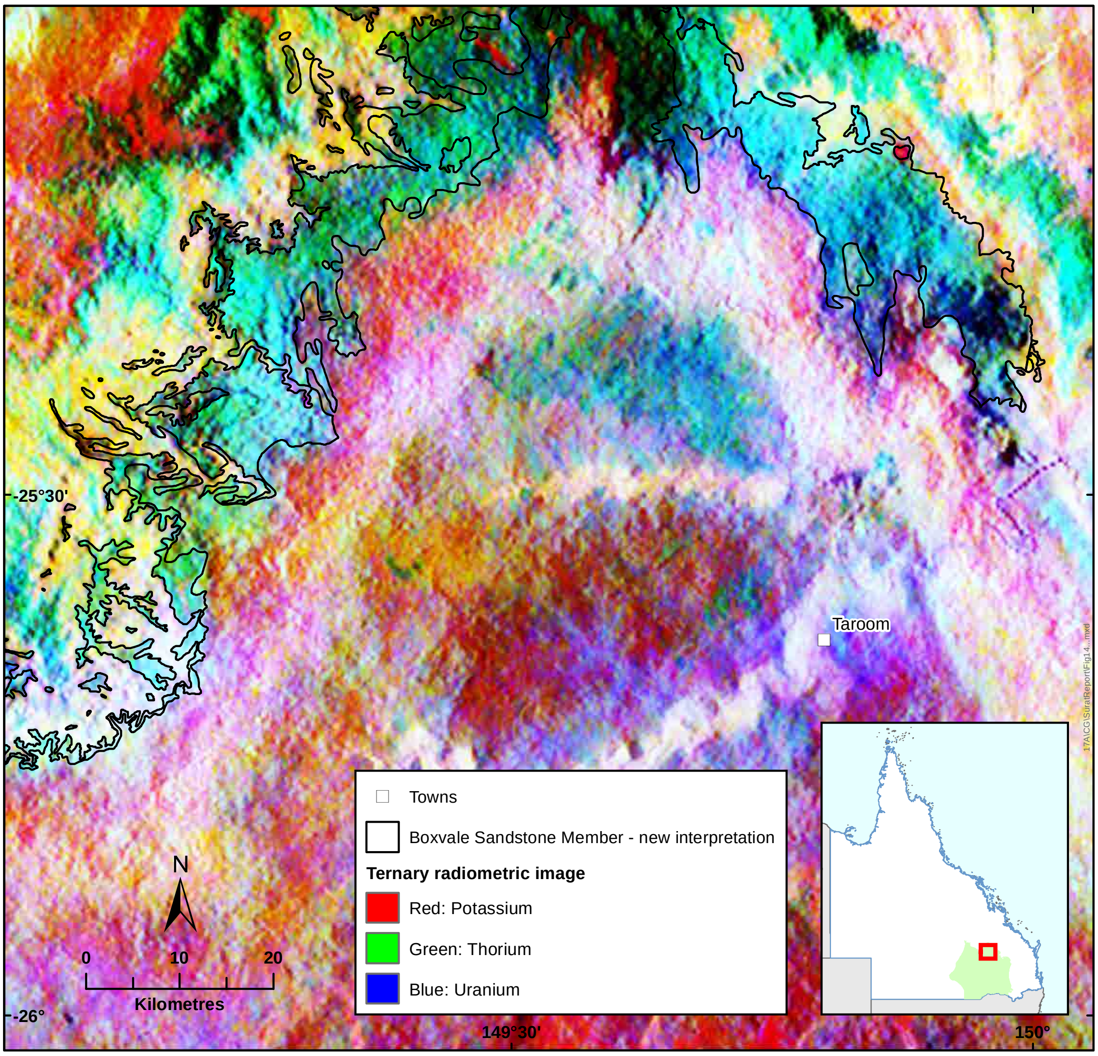


Figure 14. Boxvale Sandstone Member extent and radiometric signature.

Although such a scenario appears likely for the acritarch-bearing Boxvale Sandstone and Westgrove Ironstone Members (and adjacent other acritarch-bearing strata of the Evergreen Formation), the occurrence of brackish, lacustrine-delta systems without connection to the sea cannot be discounted.

Along the eastern and western basin margins, the Evergreen Formation has a higher percentage of sandstone than in other areas. This is interpreted to reflect the distance from the sediment supply, with the coarser sediments being deposited at first around the edges of the basin and then the finer sediments being transported to the centre (Green *et al.*, 1997).

Plate 1: Boxvale Sandstone—eastern Mimosa Syncline, approximately 20 km NE of Taroom.

Hutton Sandstone

Nomenclature

The name Hutton Sandstone was first used by Reeves (1947) who regarded the Hutton Sandstone as the top member of the 'Bundamba Series' and who used the name for the sandstones and sandy soils on Westgrove Station northwest of Injune. Mollan *et al.* (1965) redesignated the Hutton Sandstone to formation status. Mollan *et al.* (1972) nominated a type section for the Hutton Sandstone near Hutton Creek, 19 km east-northeast of Injune. The Hutton Sandstone is a very widespread unit both in the Surat and the adjacent Eromanga Basin.

Lithology

The Hutton Sandstone consists mainly of sandstone with interbedded siltstone and shale and minor mudstone and coal.

The sandstone is white to light grey, fine- to medium-grained, well-sorted, sublabile to quartzose, partly porous with some pebble bands and shale and siltstone clasts in the lower part. Siltstone and shale are light to dark grey, micaceous, carbonaceous and commonly interlaminated with very fine grained sandstone. The sandstone bed forms of the upper part of the Hutton Sandstone are characterised by low angle trough cross bedding with upward fining sequences. In the project area, an upper and a lower Hutton Sandstone unit have been recognised from their different radiometric response and texture on the radiometric and combined SPOT and digital terrain model data. Texturally, the SPOT data has demonstrated that there is no evidence that the upper unit on the western side has an equivalent on the east; however, their radiometric responses are similar. This evidence suggests a facies change along

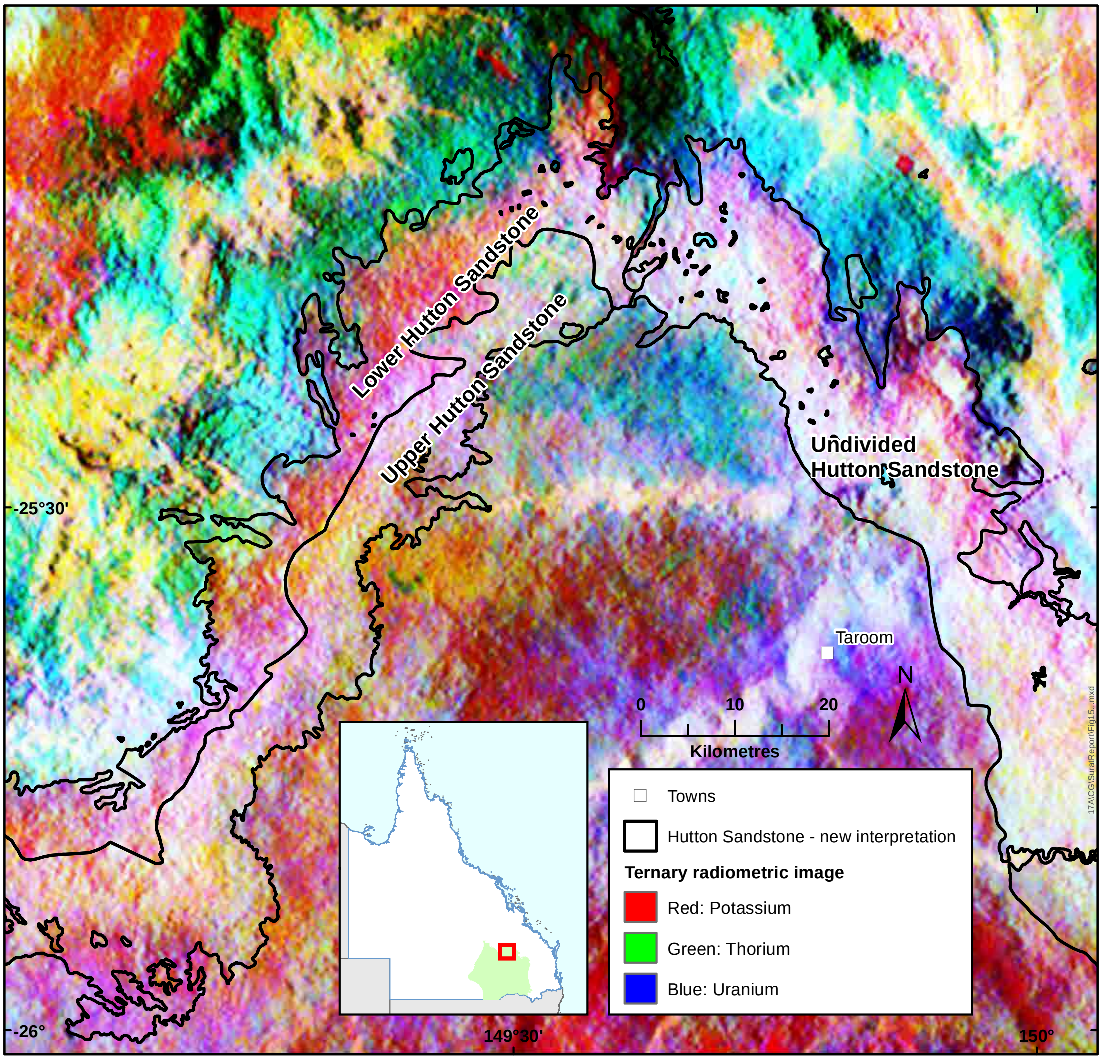


Figure 15. Hutton Sandstone extent and radiometric signature.

strike in the Hutton Sandstone on the western limb of the Mimosa Syncline. Alternatively, it could represent a provenance area change within the one fluvial system.

The variation in the Hutton Sandstone is shown in Figure 15 as undivided Hutton Sandstone, lower Hutton Sandstone and upper Hutton Sandstone.

The Plates 2 through 5 show exposures of the top and lower Hutton Sandstone on either side of the Mimosa Syncline.

Samples from these exposures were analysed using the HyLogger. The Thermal Infrared (TIR) spectrum of the samples shows that the lower Hutton Sandstone contains approximately 40–50% more quartz than the upper Hutton Sandstone (Appendix 4, Table 1). The lower Hutton Sandstone contains kaolinite, montmorillonite, possible muscovitic illite and albite. In addition to the minerals identified in the lower Hutton Sandstone, samples of the upper Hutton Sandstone also have been shown to contain microcline, confirming a granitic source.

The boundary between lower and upper Hutton Sandstone on the western limb of the Mimosa Syncline is interpreted by a change in radiometric and textural character on the digital elevation model. The upper Hutton Sandstone has a radiometric high associated with the thick, large-scale, low angle trough-cross-bedded feldspathic sublabile sandstone with minor siltstone and shale. In contrast the

Plate 2: Exposure of upper Hutton Sandstone, approximately 15km due north of Taroom.

Plate 3: Exposure of upper Hutton Sandstone, western Mimosa Syncline, approximately 30 km west of Taroom on the Taroom–Injune Road.

Plate 4: Exposure of upper Hutton Sandstone – eastern Mimosa Syncline, approximately 30 km southeast of Taroom.

Plate 5: Outcrop of lower Hutton Sandstone – western limb Mimosa Syncline, approximately 40 km due west of Taroom.

lower Hutton Sandstone is finer grained, thin-bedded, sublabile to quartz-rich sandstone with a lower radiometric response and a more rugged topography.

The lower Hutton Sandstone in the subsurface generally has a higher percentage of siltstone and shale than the equivalent in the north. In addition, a distinct 2-fold subdivision is present in some wells, reflecting the presence of a lower, mainly sublabile sandstone and siltstone subunit and an upper, more quartzose sandstone and siltstone subunit. The lower Hutton Sandstone on the western limb of the syncline is lower in Th whereas the top part has moderate Th values. Values of K are similar for the lower and upper Hutton Sandstone on the west.

The mineralogy of the Hutton Sandstone was discussed in detail by Farquar *et al.* (2013). The unit is a potential reservoir into which carbon dioxide could be sequestered, but its immature mineralogy indicates potential geochemical reactivity during such sequestration. Compositionally, the Hutton Sandstone comprises mica-rich, sublithic to quartzose, well-sorted, fine- to medium-grained sandstone, with interbedded siltstone and mudstone, rip-up clasts and pebble lags, minor coal and mudstone.

Relationships

The top of the Hutton Sandstone is taken at the top of the uppermost sublabile to quartzose sandstone below the sublabile to labile sandstones and mudstones of the Eurombah Formation, where present. The Hutton Sandstone is the most widespread Jurassic unit in the Great Artesian Basin and is continuous into, and forms the upper part of, the Marburg Subgroup in the Moreton Basin to the east. The formation extends westward into the Eromanga Basin. It appears that south of about Latitude 25.880, Longitude 150.1480, the basal Walloon Coal Measures boundary mapped in the OGIA model is close to the newly interpreted boundary of the Hutton Sandstone / Eurombah Formation. It appears likely that the Eurombah Formation is thinner on the eastern limb of the Mimosa Syncline in the outcrop area of the Taroom 1:250 000 Map Sheet. The Hutton Sandstone is overlain by Mulgildie Coal Measures in the Mulgildie Basin (an equivalent of the Walloon Coal Measures) to the northeast, near Mundubbera, and the (Durabilla) / Eurombah Formation (now shown only as Eurombah Formation herein) on the western limb of the Mimosa Syncline in the Eurombah Dome area. In the western part of the Taroom 1:250 000 Map Sheet area the unit is conformably overlain by Birkhead Formation which is apparently in part, locally equivalent to the Eurombah Formation and has been redefined as such in this report. Green *et al.* (1997) indicate that the Birkhead Formation should be restricted to the Eromanga Basin and this assertion has been accepted for this report. The Hutton Sandstone is laterally extensive across the Surat Basin, continuing to the west into the Eromanga Basin and eastwards into the Clarence–Moreton (where it is equivalent to the Heifer Creek Sandstone Member of the Koukandowie Formation of the Marburg Subgroup).

Age

Palynofloral assemblages from the Hutton Sandstone are assigned to units APJ3.3, APJ4.1 and APJ4.2 of mid-Jurassic / Aalenian–Bajocian–(?) Bathonian age (Green *et al.*, 1997; Price, 1997; McKellar, 1998, personal communication). The unit is apparently continuous with the top part of the Marburg Subgroup in the Clarence–Moreton Basin, but its top is younger than the dated top of the Marburg Subgroup (Toarcian–Bajocian) in the Clarence–Moreton Basin. This shows the common time-transgressive nature of units from east to west, from the Clarence–Moreton Basin into the Surat Basin (McKellar, 1998; Jell, (2013, figure 7)).

Wireline log character

Hauck & Edwards (Appendix 3, this report) discussed the wireline log characteristics showing the predominantly sublabile sandstones of the lower Hutton Sandstone have low to medium gamma-ray log responses that do not stand out on the resistivity log. The interbedded finer grained rocks have medium to high gamma-ray log signatures and noisy resistivity logs.

They demonstrated that the thick quartzose sandstone of the upper Hutton Sandstone have low gamma-ray and high resistivity log responses that have a sharp base and top. The interbedded siltstone and sandstone between the thicker sandstones generate noisy resistivity and moderate gamma-ray log responses. Blocky, low gamma-ray sandstones dominate the upper Hutton Sandstone and the resistivity response at the top of the formation is commonly associated with a relatively thick, low gamma-ray sandstone unit. The average baseline gamma-ray response is markedly lower than overlying formations and increases toward the base of the formation with an increasing content of siltstone. The sonic and density logs are generally quiet with faster velocities over the sandier intervals (Green, 1997).

The top of the Hutton Sandstone is recognised by an abrupt or short gradual increase in the average resistivity baseline from the overlying Walloon Coal Measures or the Eurombah/Durabilla Formation, reflecting a lithological change to quartzose sandstones. Throughout the formation the resistivity log is generally noisier than that of the overlying Eurombah/Durabilla Formation and Walloon Coal Measures.

Thickness

The maximum thickness of the Hutton Sandstone intersected in the Surat Basin is 266 m in UOD Juandah 1, close to the axis of the Mimosa Syncline (Green *et al.*, 1997). Overall the thickness of the Hutton Sandstone varies from 72 to 266 m (Gray, 2002), however, throughout most of the basin it is between 120 and 180 m thick (Exon, 1976). There is a general thickening of the Hutton Sandstone along the axis of the Mimosa Syncline and towards the north. The maximum thickness of the Hutton Sandstone can now be revised to 517.2 m in TPC Durham Ranch 9 drilled in 1999, with a more representative thickness of 394.0 m from OEC Durham Ranch 74 drilled in 1998. These wells are located approximately 80 km southwest of Taroom.

Depositional setting

The Hutton Sandstone was deposited by meandering streams on a broad continental floodplain with generally quartz-rich sediments sourced primarily from the northeast, southeast and southwest (Exon, 1976). The groundwater in the lower part of the formation commonly has a high concentration of sodium chloride, calcium sulphate and sodium carbonate. This suggests that the lower part of the formation, at least, may have been deposited in brackish water (Mollan *et al.*, 1972).

Eurombah Formation

Nomenclature

The name ‘Eurombah beds’ was first used by Exon *et al.* (1967) and Exon (1971) to describe the thickly cross bedded, fine- to coarse-grained labile to sublabile sandstones and interbedded siltstones and mudstones outcropping in Eurombah Creek, north of Roma between the Hutton Sandstone and the “Birkhead Formation” (mapped as “Undifferentiated” Injune Creek Group on the Roma 1:250 000 Sheet), which are exposed at and near the Eurombah Dome. These beds were first mapped by Jensen (1921) as “Basal Walloon” whereas Reeves (1947) included them in his Hutton Sandstone. Lithologically, they are quite different to the underlying Hutton Sandstone, the overlying Walloon Coal Measures and the ‘Birkhead Formation’ immediately to the west. They were mapped on the Roma 1:250 000 Map Sheet (Milligan & Exon, 1967). The name Eurombah Formation replaces the informal name “Eurombah beds” (Exon, 1971), which was derived from Eurombah Creek, north of Roma. Swarbrick (1973) updated the formational status to the Eurombah Formation because the unit is widespread and lithologically distinct. The type section designated in Swarbrick and Gray (1971) is from 27 to 119 m in the continuously cored stratigraphic borehole DRD 22, drilled at Latitude 26.05°S, Longitude 148.85°E., 2.5km southeast of Eurombah Homestead. The borehole is located on the southwestern flank of the Eurombah Dome (Reeves, 1935; 1947) where the formation is exposed.

The 'Eurombah beds' were not recognised during mapping of the Taroom 1:250 000 Map Sheet area to the north (Forbes & Exon, 1967), however, they are distinguished in water bores. In this study they are interpreted in the north of the Taroom 1: 250 000 Map Sheet by a combination of reported thickness from water bore data as well as having a subtle, but significantly different radiometric signature from the overlying Taroom Coal Measures. An extent for the Eurombah Formation was interpreted in the Taroom 1:250 000 Sheet area in the vicinity of the Eurombah Dome (Figure 16).

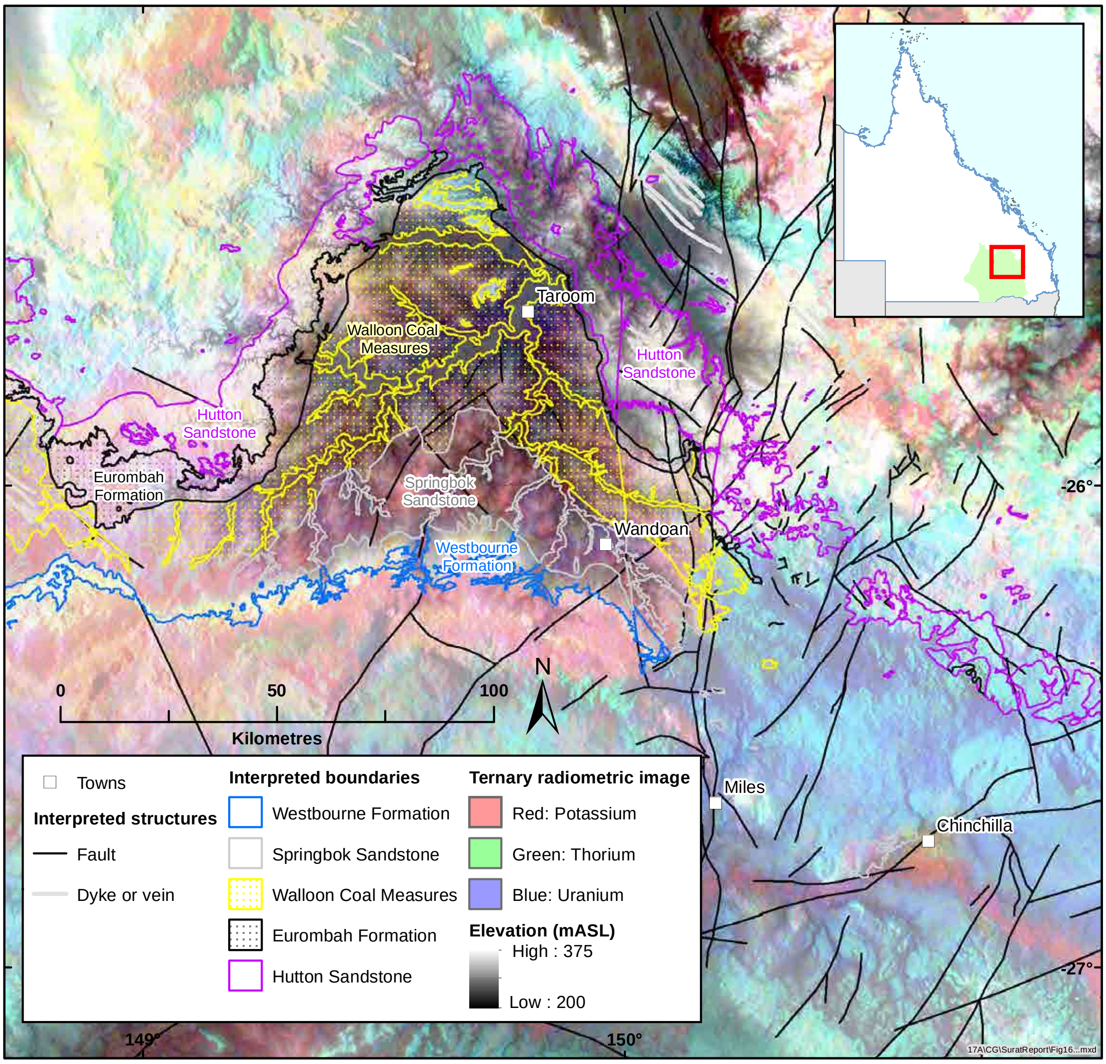


Figure 16. Ternary radiometric image draped over the 1 second digital elevation model showing the distribution of Eurombah Formation in the vicinity of the Eurombah Dome.

The presence of permeable sandstones within the Eurombah Formation in some areas makes them difficult to separate from the Hutton Sandstone on the wireline logs of most petroleum wells, and exploration companies have generally included them with the Hutton Sandstone. Exon (1971) included the Eurombah Formation in part with the Hutton Sandstone, and in part with the Injune Creek Group. Other workers (Hamilton & others, 2013, 2014) included the Eurombah Formation in the Walloon Subgroup because the outcrop character, core lithology, and lensing nature of the unit were considered more typical of this group. In this report the Eurombah Formation has been defined as a separate unit.

Scott *et al.* (2007) and Wandoan Coal joint venture (JV) (Glencore Coal Queensland Pty Limited) have suggested that the Durabilla Formation was a separate unit from the Eurombah Formation and that the Eurombah Formation underlies the Durabilla Formation. Swarbrick (1973) also recognised stratigraphic units (3 and 4) between the Eurombah Formation and the basal coal of the Taroom Coal Measures.

The Durabilla Formation, as defined by Scott *et al.* (2007), consists of amalgamated, stacked and isolated channel deposits that form a laterally continuous transition unit between the Hutton Sandstone and the Taroom Coal Measures member of the Walloon Coal Measures. This premise was rejected by Queensland Gas Company (QGC, Ryan *et al.*, 2012) who considers that the Durabilla Formation and Eurombah Formation are equivalent units.

The Eurombah Formation is definitely recognised in the vicinity of the Eurombah Dome and has been defined in water bores in northern part of the Mimosa Syncline. In contrast, CSG wells and stratigraphic boreholes from the OGIA project in the deeper parts of the basin and south of Miles, defined Durabilla Formation in the subsurface, whereas other bores log all the transitional strata as Durabilla (Figure 17).

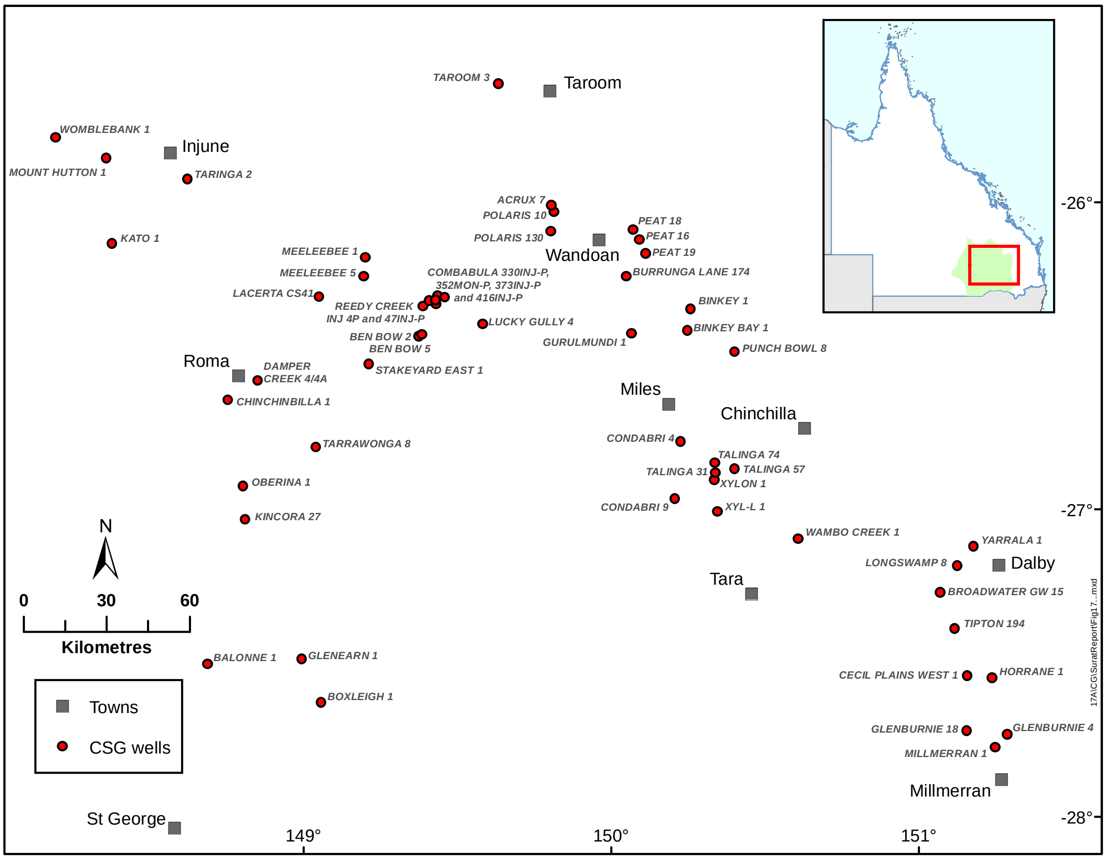


Figure 17. Locations of open file CSG wells in which the Durabilla Formation was identified.

In this report the Eurombah Formation is used in its type area around the Eurombah Dome, and along the western limb of the Mimosa Syncline, and is defined to also occur on the eastern limb of the Mimosa Syncline south of Miles. The definition of the Eurombah Formation accepted herein is based on all strata from the sequence from the top of the Hutton Sandstone and the base of the lowermost coal of the Taroom Coal Measures member of the Walloon Coal Measures, and also from the top of the Marburg Subgroup to the lowermost Taroom Coal Measures coal.

Field work in the Clarence–Moreton Basin west of Wulkuraka Railway Station near Ipswich shows a gradual transition in composition and bed forms between the top of the Marburg Subgroup and the Walloon Coal Measures. The identification of the 'Durabilla Formation' (now Eurombah Formation) in boreholes in the western margin of the Clarence–Moreton Basin shows this transition is widespread. Earlier field mapping along the eastern margin of the Main Range Volcanics interpreted 'Walloon Coal Measures' above the Koukandowie Formation (Cranfield *et al.*, 1973). This region contains little or no coal. Using the logic that non-coal transitional rock types below the basal coal unit represents the

Eurombah Formation, an area of this unit is included on the map in this area. Accordingly, an area of inferred Eurombah Formation has been interpreted in this area extending eastwards into the Clarence–Moreton Basin. An outcrop of the Eurombah Formation was examined during the final field trip and this is shown in Plate 6.

Plate 6: Cross bedded lithic labile sandstone of the Eurombah Formation (Appendix 7, Site SB17).

The outcrop comprises brown, lithic labile sandstone with cross bedding that looks similar in outcrop to Hutton, but has a different lithology. It contains abundant lithic clasts and small ironstone concretions.

Thickness

The thickness of the Eurombah Formation appears to vary greatly within the mapped area. It appears to be thickest on the western limb of the Mimosa Syncline, and in the vicinity of the Eurombah Dome. On the eastern limb the unit locally thins to approximately 20–40 m and appears to be fairly continuous along the eastern margin of the Taroom, Chinchilla, and Dalby 1:250 000 Map Sheet areas. It appears to be thinner in the domal area of the Texas Subprovince, based on limited CSG well data in that area.

The Eurombah Formation is 94 m thick in the type section (DRD 22) and 98 m thick in DRD 24, near Injune. The formation appears to thin westward, southward and eastward away from the Injune area, being 10 m thick in AAO Kildare North 1, 66 m thick in MO Wyena 1 and 43 m thick in UOD Dulacca 1. Current QPED data (2015) indicates a maximum thickness of 331.8 m in OER Talinga 81 (drilled in 2009) and a more representative thickness of 121.8 m in TOG Taringa 1 (drilled in 2000).

Distribution

At outcrop, the formation can be traced eastward from the type area into the Mimosa Syncline at least as far east as Bullock Creek on the Wandoan–Nathan road (Latitude 25.8833°S; Longitude 150.05°E). West of Injune, the formation does not appear to outcrop in the Merivale Syncline but can be picked in the subsurface in AAO Killoran 1. The unit was cored in DRD 22, 23, and 24 in the Injune area (Gray, 1972), in GSQ Taroom 3 (Swarbrick, 1971), in GSQ Roma 1 and Mundubbera 1 (Gray, 1972) in the Taroom area. In the deep subsurface, the formation can be distinguished on wireline logs of petroleum exploration wells. It can be traced from AAO Lorne1 eastward across the Roma Shelf and into the Mimosa Syncline, as far as 27°S.

Lithology

At outcrop the formation consists of more than 60 m of thickly bedded, fine to coarse, clayey, cross-bedded, labile sandstone and polymictic conglomerate and thinly bedded to laminated siltstone and mudstone. The type section in DRD 22 was described by Gray (1972) to comprise: "from 27 to 79m light green-grey to grey, very fine to very coarse, fairly and poorly sorted, subangular to subrounded, sublabile sandstone, in a white argillaceous matrix, and minor interbedded conglomerate and brown, carbonaceous mudstone. The sandstone contained many mudstone clasts; it has visibly porous in part (shown as peaks on the resistivity log). Its measured porosity averaged 21 percent; horizontal permeability ranged from nil to 18 mD and averaged 15 mD. Conglomerate, in beds to 5 inches thick, was composed of pebbles of white quartz, brown mudstone, and dark igneous material in a sandstone matrix".

From 79 to 119 m the unit is characterised by interbedded and laminated light green-grey to light grey, very fine to fine, sublabile sandstone, light grey to brown and green-grey mudstone and siltstone, in part carbonaceous, and minor pebble bands. Measured porosity of two sandstone samples averaged 20 per cent; horizontal permeability was negligible. Contact with the underlying Hutton was transitional.

Relationships

The Eurombah Formation was formerly defined as the lowermost formation of the Injune Creek Group and the Walloon Subgroup (Hamilton *et al.* 2013, 2014). It conformably overlies the Hutton Sandstone and is conformably overlain by the Walloon Coal Measures. Its lateral relationship to these units is not clear. It may become incorporated in the uppermost Marburg Subgroup in the east. It was also included (as 'Durabilla Formation') in definitions of the Walloon Subgroup of the Injune Creek Group by Hamilton *et al.* (2013), but for the reasons stated above is separated from the Walloon Coal Measures in this project. The lower boundary of the Eurombah Formation is defined as the top of the channel sand or coarse pebbly band of feldspathic sandstone at the top of the Hutton Sandstone and / or a similar band at the top of the Koukandowie Formation (Marburg Subgroup). The upper boundary of the Eurombah Formation is defined as the base of the lowermost coal of the Taroom Coal Measures member at the base of the Walloon Coal Measures.

Distinguishing characteristics

Sandstones of the Eurombah Formation are intermediate in colour between those of the Hutton Sandstone (white to light grey, weathering to yellow-brown) and those of the Walloon Coal Measures (dark grey to green, weathering to grey-brown). The Eurombah Formation contains thickly bedded, cross-bedded, coarse sandstone, pebbly sandstone and conglomerate, which are rare in the Hutton Sandstone and Walloon Coal Measures sequences. The sandstones are more labile than those of the Hutton Sandstone and less labile than those of the Walloon Coal Measures. In contrast to the overlying Walloon Coal Measures, the Eurombah Formation is non-calcareous. The clay matrix in sandstones of the Eurombah Formation is white, but is yellow in those of the Walloon Coal Measures (Gray, 1972). Porosity of sandstones varies greatly and randomly in the Eurombah Formation and depends on the presence of matrix.

Wireline log character

On wireline logs the top of the Eurombah Formation is frequently difficult to recognise. The true lithological top is often some metres higher than the highest porous sandstone (which is easily identified on resistivity logs). In the type section (DRD 22) the true top is taken as being 22 m above the highest significantly porous sandstone. The base was identified at the top of the highest resistivity peak of the Hutton Sandstone type, below which the log does not return to the Walloon Coal Measures baseline for a considerable depth (Gray, 1972).

An update on the wireline log characteristics of the unit is given in Hauck & Edwards (Appendix 3, this report). They show that it is characterised by blocky low gamma-ray sandstones and abundant thin mudstones and carbonaceous units that give a high gamma-ray response. The overall gamma-ray response is less variable and features more subdued, gradual fining-up or fining-down sequences than the overlying coal measures. Irregular and infrequent low density coaly intervals are contrasted against a relatively flat, non-variable density baseline.

Environment of deposition

The environment of deposition of the Eurombah Formation was interpreted to be mainly fluviatile with periods of rapid sedimentation.

The low degree of size sorting suggests rapid sedimentation. Increases in the proportions of lithic and feldspar grains upwards suggest a provenance area not eroded during the deposition of the Hutton Sandstone that began supplying immature sediment to the northern Surat Basin during deposition of the Eurombah Formation. The rigorous reworking conditions which applied during the deposition of the Hutton Sandstone gave way to the sluggish conditions, which then applied during the deposition of the Walloon Coal Measures. The Eurombah Formation apparently represents a transitional facies stage between the Hutton Sandstone and the Walloon Coal Measures related to a gradual change in source area from the Hutton Sandstone to the Walloon Coal Measures.

Fossils and age

In the Surat Basin, Green *et al.* (1997) included the Eurombah Formation in the Walloon Coal Measures, as the Eurombah Formation could not be consistently identified in the subsurface, although the formation has since been variously recognised by others authors (e.g., Scott *et al.*, 2007). As such, palynofloras are associated with palynological units AP4.3–APJ4.3 (Price, 1997; McKellar, 1998; Jell, 2013, figure 7.2). A mid-Jurassic/Bathonian age has been indicated (McKellar, 1998; Jell, 2013, figure 7.2).

Comments

Amalgamated, stacked and isolated channel deposits form a laterally continuous transition unit in the Eurombah Formation. Checking of the Australian Stratigraphic Units Database entry for the Eurombah Formation provides a reference from Swarbrick (1973) to a type section for the Eurombah Formation adjacent to the Eurombah Anticline on the northern margin of the Roma Sheet. Conversely there is no adequately defined top and bottom of the Durabilla Formation which has an informal status. Consequently, in this report the whole of the fine-grained sediment between the top of Hutton Sandstone – Marburg Subgroup and the lowermost coals of the Taroom Coal Measures is herein defined as Eurombah Formation.

Walloon Coal Measures

Nomenclature

Cameron (1907) used the name Walloon beds for the strata outcropping in the Walloon, Rosewood and Dugandan districts of the Clarence–Moreton Basin. Reid (1921) changed the name from Walloon beds to Walloon Coal Measures when he mapped the Walloon–Rosewood Coalfield. Whitehouse (1955) nominated the type area as the mining region about the township of Walloon. The type section was designated by Cameron (1970) from 7 m to 235 m in drill hole N.S. 84 in the Ebenezer district.

The definition of the Walloon Coal Measures in a more regional sense as required in this project attempts to define the sequence based on the first occurrence of economic coal above the top of the Eurombah Formation or alternatively, the top of the Hutton Sandstone, or the top of the Marburg Subgroup, if the Eurombah Formation is not present. This definition is suitable as it has a clearly defined target. The target can be defined through the basal coal resources of the Taroom Coal Measures that can be identified through the result of drilling to form the base of the coal measures. The top of The Walloon Coal Measures can be defined by the unconformity at the base of the Springbok Sandstone. Under this definition, strata included in the Eurombah Formation (including, in particular, the Durabilla Formation) would be excluded from the Walloon Coal Measures. This contrasts with recent work by University of Queensland workers (e.g. Hamilton *et al.*, 2013, 2014) who include the Durabilla Formation into the Walloon Subgroup of the Injune Creek Group. The term Injune Creek Group is not used in this report and the Walloon Coal Measures is regarded as a formation.

For the purpose of this study the Walloon Coal Measures is defined from the basal coal of the Taroom Coal Measures to the top of the Springbok unconformity (SPUNCON).

Lithology

In the Surat Basin, the Walloon Coal Measures in the subsurface consist of very fine to medium-grained, labile, argillaceous sandstone, siltstone, mudstone and coal, with minor calcareous sandstone, impure limestone and ironstone (Swarbrick, 1973). Under Swarbrick's definition the coaly sequence is located in the upper half to three-quarters of the measures, with mudstones, siltstones and lithic sandstones dominant in the lower part. In the northeastern Surat Basin, he subdivided the Walloon Coal Measures into six lithostratigraphic units. On the basis of this subdivision, Jones & Patrick (1981) raised the Walloon Coal Measures to Subgroup status, and in stratigraphic order formally defined the Taroom Coal Measures, the Tangalooma Sandstone, and the Juandah Coal Measures. This definition of the Walloon Coal Measures is important as it defines two coal producing units separated by a non-coaly sequence. Gallagher (2012) asserts that lithostratigraphic correlation of open-file industry and government wireline logs supports the interpretation of six subunits in the eastern Surat Basin (oldest–youngest: Durabilla Formation; Taroom Coal Measures; Tangalooma Sandstone; and Juandah Coal Measures, informally divided into three members named the lower Juandah Coal Measures, Juandah Sandstone and upper Juandah Coal Measures). Most of these subunits cannot be uniquely identified and mapped through the area and only the Walloon Coal Measures is shown on the accompanying surface and solid geological map (Appendices 1 and 2). Plate 7 shows an outcrop of basal Walloon Coal Measures ('Taroom Coal Measures member') north of Taroom.

It is an important finding of this study that subunits within the Walloon Subgroup do not correlate along the entire CSG play area. Furthermore, in many places, the overlying Springbok Sandstone (Upper Jurassic) has incised to the lower Juandah Coal Measures level, removing the upper coal seam groups. The units do not appear to be laterally continuous. Consequently, the Walloon Coal Measures is better considered to be more formational status and the units defined by Jones & Patrick (1981) to be members.

Plate 7: Walloon Coal Measures (Taroom Coal Measures), 15 km north of Taroom.

The Taroom Coal Measures member comprises a mixed sequence of sandstone, siltstone and mudstone, with abundant coal and carbonaceous mudstone interbeds (Scott *et al.*, 2004). A mixed assemblage of sandstone, siltstone, mudstone, claystone, tuff and thin coal to carbonaceous mudstone seams/beds form the Tangalooma Sandstone member (Rohead-O'Brien, 2011). The sandstone is commonly heavily cemented or infilled with clay (Rohead-O'Brien, 2011). The Juandah Coal Measures member is similar in composition and coal volume to the Taroom Coal Measures (Scott *et al.*, 2004).

West of approximately longitude 148.5°E, the percentage of coal in the Walloon Coal Measures decreases markedly (Green *et al.*, 1997).

Samples of outcrop in the Taroom 1:250 000 Sheet area from the Walloon Coal Measures were analysed using the HyLogger. Short-wave infrared (SWIR) minerals include montmorillonite, calcite and siderite from samples at Latitude 25.974°S, Longitude 149.987°E, and Latitude 25.634°S, Longitude 149.69°E, and lesser kaolinite from samples at Latitude 25.92°S, Longitude 148.549° E, Latitude 25.661°S, Longitude 149.423°E and Latitude 25.662°S, Longitude 149.353°. Quartz in the Thermal Infrared (TIR) is less than 25% (e.g. sample from Latitude 25.661°S, Longitude 149.353°E) with some samples (Latitude 25.974°S, 149.987°E and Latitude 25.634°S, 149.69°E,) not containing any detectable quartz (Appendix 4, Table 1). The occurrence of montmorillonite is similar to HyLogger data for the Walloon Coal Measures in GSQ Roma 7.

Relationships

The Walloon Coal Measures conformably overlie the Eurombah Formation as adopted herein. New interpreted boundaries and relationships are shown in Figure 12 and Figure 16.

The Walloon Coal Measures were defined as laterally continuous with the Birkhead Formation of the Eromanga Basin, however the Birkhead Formation has little or no coal. Swarbrick (1973) placed the boundary between the two formations in the western part of the Surat Basin between Injune and the eastern flanks of the Nebine Ridge. In this report, it was not possible to draw a boundary between the two formations in the cross-sections. Instead, the boundary was found to be transitional in agreement with Green *et al.* (1997) who indicated that the name Birkhead Formation should be restricted to the Eromanga Basin. This approach has been followed in this study of the Surat Basin.

The top of the Walloon Coal Measures was taken at the topmost coal or thick mudstone interval below the unconformity to sandstones of the Springbok Sandstone (Green *et al.*, 1997). For the purpose of this project the definition of Green *et al.*, (1997) was accepted as a practical method of creating a map for this unit even though some CSG companies, for instance APLNG does not use the top coal of the Walloons to define the unit top except in areas where the Springbok has eroded down into the coals.

Wireline log character

The Walloon Coal Measures exhibits low average resistivity log values, high gamma-ray log values and a noisy sonic log with slow velocities owing to the coal seams (Green *et al.*, 1997). Hauck & Edwards (Appendix 3, this report) recognise the top of the Walloon Coal Measures by a relatively thick unit of high gamma-ray mudstone or siltstone differentiated from the blocky, low gamma-ray channel sandstone at the base of the Springbok Sandstone. Where the baseline increase in the gamma-ray log is not readily apparent, they pick the top of the Walloon Coal Measures at the top of the uppermost coal below the sandstone base of the overlying Springbok Sandstone.

Thickness

The maximum thickness of the Walloon Coal Measures intersected is 462.9 m in UOD Dulacca 1, in the axial part of the Mimosa Syncline, west of Miles from the Queensland petroleum exploration database (QPED GSQ stratigraphy extract). The formation thins to the southwest and onlaps the Roma and Walgett Shelves (Green *et al.*, 1997). Current QPED data (2015) places a maximum thickness of 524.81 m in ARM Silverdale 3A (drilled in 2005), with a more realistic thickness of 453.34 m in AEL Harrisville 1 (drilled in 2009).

Age

Based on the affinities of a macroflora from the Walloon Coal Measures in the Clarence–Moreton Basin with a flora from the well-dated Clent Hills Group of New Zealand, the formation / subgroup (including its equivalents in the Surat and Mulgildie Basins) have been considered to be Bajocian–Bathonian in age (Grant-Mackie *et al.*, 2000). Palynological evidence has favoured a Bathonian–Callovian age and has pointed to: (1) the base of the formation younging from the Surat Basin into the Clarence–Moreton Basin; and (2) the existence of widespread unconformity at the formation's / subgroups top (McKellar, 1998). The existence of this hiatus was subsequently corroborated by Scott *et al.* (2007). In terms of Price's (1997) zonal units, palynofloras of the Walloon Coal Measures are conformable with APJ4.2, APJ4.3 and APJ5. However, recent CA-IDTIMS dating of the Walloon Coal Measures in the Surat Basin has pointed to deposition of the Walloon Coal Measures extending into the early Late Jurassic / Oxfordian (Wainman *et al.*, 2015).

Depositional setting

Most of the Walloon Coal Measures were deposited as coal swamps with the lower part comprising mainly over bank deposits (Exon, 1976). McLean-Hodgson & Kempton (1981) concluded that the Walloon Coal Measures were deposited in a high sinuosity fluviatile environment dominated by meandering streams. Clark & Cooper (1985) interpreted the depositional environment of the Walloon Coal Measures from core in GSQ Dalby 1 and GSQ Chinchilla 3, to be a fine-grained meander-belt river system.

Springbok Sandstone

Nomenclature

Exon (1966) referred to the sandstones outcropping in the uppermost Birkhead Formation southwest of Injune as the 'Springbok Sandstone Lens'. Exon *et al.* (1967) renamed the unit the Springbok Sandstone Member when its extent in the Surat Basin became known. Power & Devine (1968) raised the unit to formation status following a regional subsurface study of the Surat Basin. The lower part of the Springbok Sandstone appears to be equivalent to the 'Proud Sandstone', a name used by Mines Administration Pty Ltd in the Roma area in the early 1960s and sometimes applied by Santos to the interpretation of Surat Basin coal seam gas wells.

Lithology

In the stratigraphic borehole GSQ Taroom 7 in the western Mimosa Syncline, the Springbok Sandstone is characterised by porous, permeable and friable sandstones. The lowermost 6 m in GSQ Taroom 7 consists of very coarse grained to pebbly quartzose sandstone with an erosional base (Swarbrick, 1973).

Gallagher (2012) showed in the type section from 38 m to 50 m in BMR Mitchell 3 and in various GSQ stratigraphic boreholes, the Springbok Sandstone consists dominantly of feldspathic sublabile to lithic sandstones, commonly with a calcareous cement. The sandstones are very fine to coarse-grained, although some are very coarse grained poorly sorted, and pebbly beds also occur. Minor interbedded siltstones and mudstones and thin coal seams are also present, mainly in the upper part of the unit.

Outcrop of the Springbok Sandstone observed along the Condamine River and its tributaries on the Chinchilla 1:250 000 Sheet area comprised feldspatholithic cross-bedded sandstone with minor siltstone with sporadic occurrences of fossil wood. In this area the outcrop is strongly lateritised.

From the radiometric imagery and analysis by the hand held Niton XRF analyser the Springbok Sandstone differs from the overlying Westbourne Formation by having lower higher Th and K values (Figures 9 and 10).

In outcrop in the Taroom 1:250 000 Map Sheet area, the Springbok Sandstone comprises a sequence of feldspatholithic labile to sublabile sandstones. The sequence also contains interbedded siltstones, shales and mudstones with some coal layers. A faulted exposure of Springbok Sandstone coal in a road cutting was recorded in the vicinity of Latitude 26.365°S; Longitude 150.074°E on the Miles to Taroom road (Plate 8). Locally, an unconformable layer of gravel overlies the Springbok Sandstone in this sheet area (Plate 9, 26.134°S; 149.773°E). This cover appears to be very thin and the resolution of the radiometric data is inadequate to define the extent of this cover. The coal layers in the Springbok Sandstone differ from those of the Walloon Coal Measures in that they contain significant amounts of inertinite. Plate 10 shows an erosional gully near Injune (Latitude 25.987°S; Longitude 148.653°E).

Relationships

Exon (1976) proposed that the Springbok Sandstone conformably overlies the Walloon Coal Measures. New boundaries and relationships are presented in Figure 12 and Figure 13. However, the appearance of scouring at the base in some areas, and the fact that sandstones from the Walloon Coal Measures and the Springbok Sandstone are lithologically different influenced Green *et al.* (1997) to propose an unconformity. Deposition of the Springbok Sandstone represents the start of the third major sedimentary cycle in the Surat Basin. The Springbok Sandstone has no correlative in the Clarence–Moreton Basin. It is laterally equivalent to but not continuous with the Adori Sandstone in the Eromanga Basin (Green *et al.*, 1997). The Adori Sandstone is generally more quartzose than the Springbok Sandstone. In the southern part of the Surat Basin, the Springbok Sandstone interfingers with the lower part of the Pilliga Sandstone in the Queensland / New South Wales border region (Exon, 1976), and in the east forms the lowermost part of the Kumbarilla beds.

Plate 8: Coal outcrop in Springbok Sandstone with minor fault offset indicated by red line.

Plate 9: Tertiary Cobble Conglomerate unconformably overlying Springbok Sandstone; minor fault offsets.

Plate 10: Erosion gully in the Springbok Sandstone, approximately 15 km southeast of Injune.

HyLogger data from outcrop samples in the Taroom 1:250 000 Map Sheet area shows the formation of kaolinite, montmorillonite, dickite, calcite and siderite in the SWIR (short-wave infrared) and kaolinite, quartz, and locally microcline, oligoclase and orthoclase, and illite are present in the TIR (thermal infrared) spectra (Appendix 4, Table 1). In the samples collected from the Taroom 1:250 000 Map Sheet area for this study the quartz content is higher (>30%) than in the Walloon Coal Measures.

Shallow sonic boreholes were drilled for a study by Douglas and Partners (2015) southwest of Chinchilla (Figure 18) to investigate the nature of the alluvium above the Springbok Sandstone. Levels of measured methane in the subsurface associated with the Springbok Sandstone along the Condamine River and Charley's Creek close to known zones of gas discharge to the Condamine River south west of Chinchilla were also investigated.

The nature of the Springbok Sandstone in this area varies from lithic to quartz-rich sandstones and claystone with only rare carbonaceous layers. All the boreholes analysed for the Douglas and Partners investigation had very high concentrations of methane (CH_4). Cousin 1 (Latitude 26.812844°S, Longitude 150.483091°E) had CH_4 recorded at 1950 ppm. Welke 1 (Latitude 26.903021°S, Longitude 150.5475°E) recorded CH_4 at greater than 24,000 ppm and Purnell 1 Latitude (26.800166°S, Longitude 150.5475°E) recorded CH_4 at greater than 50,000 ppm.

Cousin 1 and Welke 1 are located close to a fault structure along the Condamine River which has been interpreted in this study from magnetic data. The highest methane values were recorded in the basal part of the Purnell 1 investigation borehole, which is located close to the boundary of two fault structures that lie along the Condamine River and Charleys Creek. The Purnell 1 borehole was ultimately plugged and abandoned due to its high methane levels. The other boreholes drilled for the Douglas Partners investigation (namely Welke 2, Welke 3 and Pascoe 1) have lower methane emissions and are not directly associated with structures interpreted by this current study.

Wireline log character

The Springbok Sandstone is characterised by relatively low gamma-ray and high average resistivity log values comparable with the underlying Walloon Coal Measures. In some wells the boundary between the Springbok Sandstone and the overlying Westbourne Formation is transitional and difficult to pick, especially if the lowermost Westbourne Formation is sandy. In these wells, the change in the gamma-ray log baseline from low to high values probably denotes the top of the Springbok Sandstone. It is possible however that the increase in gamma-ray log values seen in the lowermost Westbourne Formation in SOC Bogong 1 is due to an increase in K-feldspar in the sandstone and the boundary with the Westbourne Formation is higher and corresponds to a decrease in the resistivity log above 1000 m (Green *et al.*, 1997). Hauck & Edwards (Appendix 3, this report) commented that the basal Springbok Sandstone has a higher resistivity log response than sandstones in the underlying Walloon Coal Measures and was used to define the boundary in many areas where the unit is thin. The average baseline of the sonic log is higher over the Springbok Sandstone than the underlying coal measures and

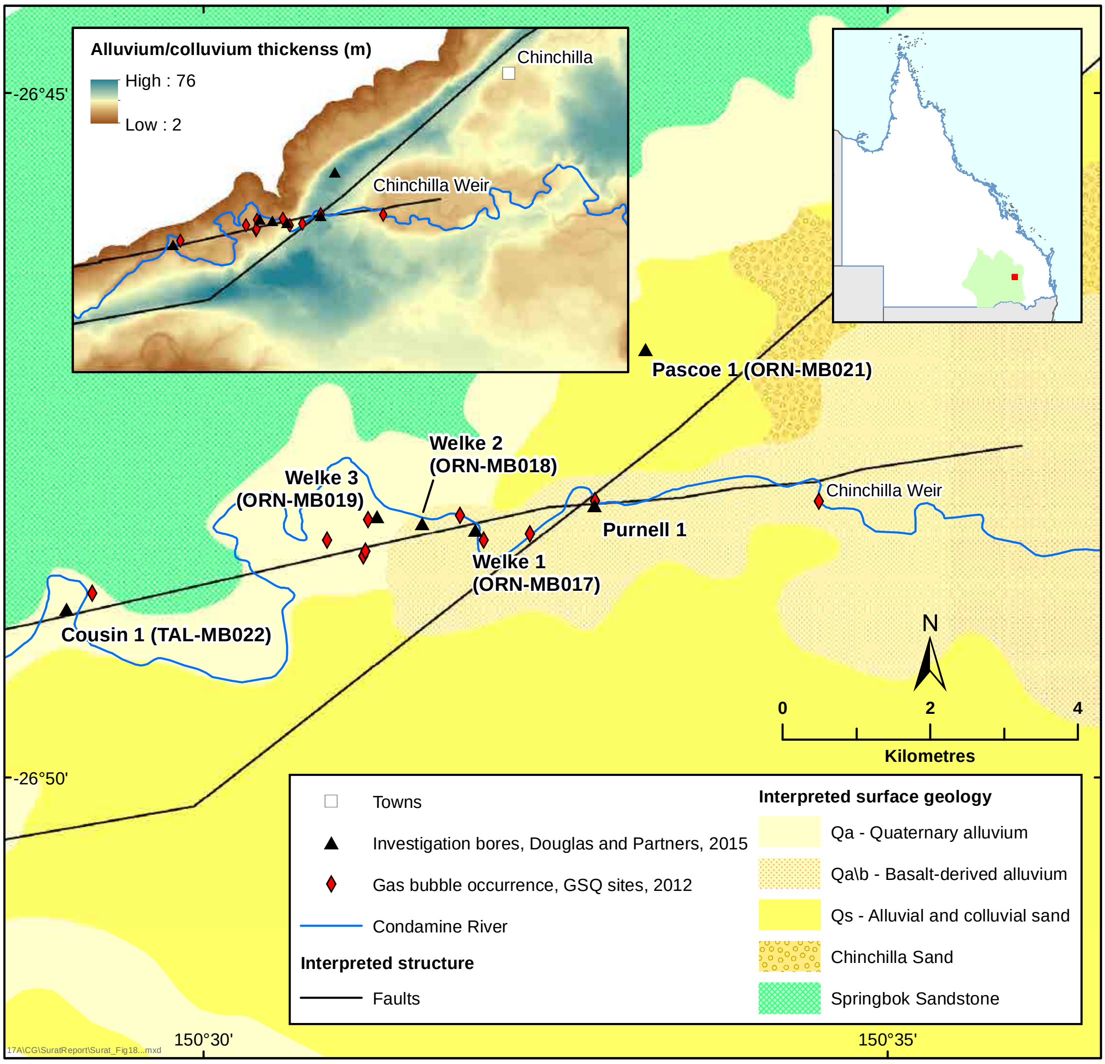


Figure 18. Location of the Douglas and Partners investigation boreholes and of methane seeps in the Condamine River.

is higher still over these coarser lower sands. This lower Springbok Sandstone unit of coarser sand is equivalent to the Proud Sandstone of the Roma area (Green, 1997).

Hauck & Edwards (Appendix 3, this report) also indicated that the Springbok Sandstone is generally characterised by a relatively low gamma-ray response compared to the finer grained sediments in the overlying Westbourne Formation and underlying Walloon Coal Measures. The gamma-ray log highlights the variable lithic to quartzose composition of the sandstones. In some wells, the lowermost part of the Westbourne Formation is sandy and the boundary between the Springbok is transitional. In these wells the top of the Springbok Sandstone can be picked where there is an increase in the gamma-ray baseline. For consistency it is suggested that the top of the Springbok Sandstone be picked where the siltstone and mudstone units begin to dominate both the gamma-ray and resistivity logs.

Thickness

The maximum thickness of Springbok Sandstone intersected in wells was stated at 157 m in UOD Flinton 1 in the southern part of the Mimosa Syncline (Green *et al.*, 1997). The Springbok Sandstone has an uneven thickness trend across the Surat Basin with no apparent main depocentre (Green *et al.*, 1997). Consistent thinning towards the margins seen in the underlying formations is not readily apparent in this unit (Green *et al.*, 1997). The lack of any apparent trend in change of thickness probably reflects the difficulty in picking the top of the formation in some wells, as discussed above, resulting in inconsistent thicknesses (Green *et al.*, 1997). This has been refined by Hauck & Edward (2016, Appendix 3, this report). Current QPED data from 2015 indicates a maximum thickness of 338.13 m in OCA Tchanning 1 (drilled 2003), and a more representative thickness of 254.27 m in QGC Pinelands 6 (drilled in 2010).

Age

Palynofloras associated with the Springbok Sandstone are associated with unit APJ5 and were considered by McKellar (1998) to be Oxfordian. In the adjacent Eromanga Basin, the lithostratigraphically equivalent Adori Sandstone, which intertongues with the Springbok Sandstone on the Nebine Ridge (Exon, 1976), contains palynofloras attributable, in places, to APJ5, but largely to APJ6, the latter indicating unconformity between the Springbok Sandstone and the underlying Birkhead Formation (an equivalent of the Walloon Coal Measures). Oxfordian isotopic dates obtained from the Walloon Coal Measures in the Surat Basin indicate that the formation is younger than previously thought (Wainman *et al.*, 2015). The Springbok Sandstone has been dated isotopically and publication of a revised age range for its deposition is pending.

Depositional Setting

Deposition of the Springbok Sandstone was mainly by streams with some overbank and swamp deposits in the upper part of the unit indicating that streams became less energetic with time (Exon, 1976). Sediment transport was mainly towards the centre of the basin. Lithic sandstones present in the Springbok Sandstone, derived from the north and east, indicate contemporaneous volcanism, whereas in the south, sandstones are more quartzose suggesting sediment supply from a predominately granitic terrain (Green *et al.*, 1997). Evidence from the present project indicates the source would be the granitic rocks from the Yarraman and Auburn Subprovinces.

Westbourne Formation

Nomenclature

The Westbourne Formation was defined by American Overseas Petroleum Ltd (1964) with the type section from 389 m to 503 m in drill hole AOP Westbourne 1 well south of Tambo, in the Eromanga Basin (Green *et al.*, 1997). A modified version, incorporating field work, was published in Exon (1966).

A well-developed mudstone, sandstone, siltstone and coal unit, the Norwood Mudstone Member forms the lower part of the Westbourne Formation over much of the Surat Basin (Swarbrick *et al.*, 1973).

Samples taken from the Westbourne Formation from the core GSQ Roma 7 were analysed using a hand held Niton XRF analyser. The samples from immediately above the top of the Springbok Sandstone showed characteristically high Th levels similar to the Th levels identified using the airborne radiometric data set.

Lithology

In the type section in AOP Westbourne 1 in the Eromanga Basin, the formation consists of 114 m of interbedded shales and siltstones and very fine grained, quartzose sandstones. In the Surat Basin, the formation is similar but contains a higher proportion of sandstone (Green *et al.*, 1997). The unit was poorly exposed in the Taroom 1:250 000 Map Sheet area however, a sample was collected at site 43 (Latitude 26.1850 S; Longitude 149.2120E) for XRF analysis using the hand held Niton XRF analyser. This outcrop sample plotted in the same field as the core samples. In outcrop and from borehole GSQ Roma 7 the Westbourne Formation is high in Th differing it from the underlying Springbok Sandstone.

The shales in the basal part of the unit are commonly light grey and green-grey, laminated to thinly bedded. Minor roots and burrows are present. Rare coal laminae are associated with root development (Green *et al.*, 1997). The siltstones are light grey to grey, well sorted and laminated to thinly bedded. Erosive bases to beds and ripple laminations are common. Minor carbonaceous material and bioturbation are also present (Green *et al.*, 1997). This is well demonstrated in core photos, Plates 1, 2, 3 and 5 in Appendix 5.

The sandstones are very fine to medium-grained, in part very coarse-grained, fairly to poorly sorted, and sublabile to quartzose. Bedding is massive with medium cross-beds present in places. Sandstones are better developed along the eastern margin of the basin with thick porous beds present in GSQ Dalby 1. An argillaceous, in part chloritic matrix and a minor calcite cement are present. Rare coal fragments and rip-up clasts also occur (Green *et al.*, 1997).

On the Roma and Walgett Shelves the proportion of sandstone also increases towards the south and west respectively (Green *et al.*, 1997).

The type section of the Norwood Mudstone Member (lowermost Westbourne Formation) in GSQ Roma 7 on the western side of the Mimosa Syncline consists of interbedded mudstone and fine- to coarse-grained lithic labile sandstone with minor siltstone and coal. The sandstone generally fines upwards and increases in quartz content. The coal areas are now considered as being the top of the Springbok Sandstone (Green *et al.*, 1997).

HyLogger data for samples of the Westbourne Formation (Norwood Mudstone) as part of the current study comprise kaolinite and montmorillonite in the SWIR and, additionally, some quartz in the TIR. The results from XRF analysis of these Westbourne Formation samples are provided in Appendix 4, Table 1.

Relationships and boundary criteria

The Westbourne Formation, although defined in the Eromanga Basin, is recognised throughout the Surat Basin in the subsurface. According to Green *et al.* (1997), the Westbourne Formation cannot be recognised in outcrop further east than approximately Longitude 148.91°E. This assertion is at odds with the radiometric signature that indicates it continues much farther east and south of what was previously mapped. New boundaries and relationships are shown in Figure 13. Westbourne Formation is also identified in coal and petroleum boreholes in these areas.

The Westbourne Formation and underlying Springbok Sandstone both intertongue with, and grade into, the Pilliga Sandstone in the south, close to the Queensland / New South Wales border (Exon, 1976) at the southern margin of the project area.

Wireline log character

The Westbourne Formation typically has low average resistivity and gamma ray log values that generally increase towards the top of the formation reflecting increasing mudstone/siltstone content (Green *et al.,* 1997). The gamma-ray log response of the siltstone is generally the highest of all the Jurassic formations in the Surat Basin which is a characteristic of the Westbourne Formation in the Eromanga Basin (Green *et al.* 1997).

Hauck & Edwards (Appendix 3, this report) showed that the Westbourne Formation is typified by low resistivity log values, except over the sandstone units which have moderate resistivity. Sonic logs over the Westbourne Formation are highly variable depending on the amount of mudstone/siltstone present in the formation but have a slightly higher average baseline than those over the Springbok Sandstone and may show increases in velocity towards the top of the formation.

The gamma-ray log values are uneven but tend to increase toward the top of the Westbourne Formation, reflecting increasing mudstone/siltstone content, which is terminated by the lower, less noisy gamma-ray baseline of the overlying Gubberamunda Sandstone. The sharp contrast between the gamma-ray logs produced by these two formations defines the top of the Westbourne Formation and provides a useful regional marker.

Thickness

The maximum thickness of Westbourne Formation intersected in the study wells of Green *et al.* (1997) was 220 m in UOD Cabawin 1 along the eastern side of the southern Taroom Trough. Green *et al.* (1997) noted additional depocentres for the Westbourne Formation in the northeast and north of the Surat Basin, with the axis of deposition trending northwestwards. Exon (1976) noted that the thickness of the Westbourne Formation in the Surat Basin ranges from less than 100 m in the west to over 250 m in the east.

The interval from the base of Springbok Sandstone to the top of the Westbourne Formation commonly displays a relatively constant thickness in adjacent wells whereas the thicknesses of the individual formations may vary greatly. This may be explained by the two units representing two facies of the same fluvial cycle (Green *et al.*, 1997). Current QPED data (2015) places a max thickness of 328.02 m in QGC Arvin 1 (drilled in 2008) with a more representative thickness of 311.18 m in QGC Lauren 68 (drilled in 2009).

Age

The Westbourne Formation encompasses continental palynofloras conformable with units APJ5 and APJ6 (Green *et al.*, 1997). An Oxfordian–Kimmeridgian–Tithonian age range has been indicated with the base of the formation being generally younger in the Eromanga Basin (McKellar, 1998; Jell, 2013, figure. 7.2). However, revision of this age for the formation is pending following CA-IDTIMS age dating. No further definitive age studies have been undertaken on this unit.

Depositional setting

The Westbourne Formation was interpreted by Exon (1966) to have been deposited in a lacustrine environment. In the Augathella area of the eastern Eromanga Basin Shield (1991) described the environment of deposition as being characteristic of a lacustrine deltaic plain which is supported by the presence of thin coal and oolite beds. Algal palynomorphs suggest that environmental conditions were partly lacustrine (Green *et al.*, 1997).

The isopach map of the Westbourne Formation in the Surat Basin in Green *et al.*, (1997) suggests that the streams feeding the deltas and lake systems flowed to the northeastern and northern parts of the basin. The Norwood Mudstone Member was considered to be deposited in a low energy, back-swamp environment with associated meandering stream channels (Swarbrick *et al.*, 1973).

Gubberamunda Sandstone

Nomenclature

Reeves (1947) was the first to use the name Gubberamunda Sandstone for the porous ridge-forming sandstones outcropping north of Roma that yield large artesian water flows from bores over much of the Surat Basin. The formation was formalised by Day (1964) and the type area is near Bungil Creek, approximately 35 km north of Roma (Green *et al.*, 1997).

Lithology

In the type area, the Gubberamunda Sandstone comprises predominantly medium- and coarse-grained, virtually uncemented quartzose sandstones. Exon (1976) considered the unit to consist of quartzose to sublabile, poorly sorted sandstone with lesser conglomerate, siltstone, mudstone and claystone. In stratigraphic borehole GSQ DRD26 northwest of Roma, the Gubberamunda Sandstone consists of nearly equal amounts of sandstone and thinly bedded and laminated sandstone, siltstone and shale (Gray, 1972). The sandstones contain minor nodular pyrite.

Outcrop of the unit 35 km north of Wallumbilla in the study area comprises poorly cemented sublabile to quartzose sandstone with rare pebble layers (Plate 11, 26.2736°S, 149.2571°E). Additional exposures of this unit were observed during the final field trip in October 2016 (Appendix 7).

HyLogger spectra from outcrop collected from Latitude 26.261°S; Longitude 149.257°E show kaolinite and montmorillonite in the SWIR and relatively high quartz (locally up to 47% in the TIR) with a recording of illite and albite. Responses for Gubberamunda Sandstone samples analysed using the Niton hand held XRF are generally low both in outcrop (Figure 10) reflecting the lack of feldspar in the unit.

Relationships

Regionally, the Gubberamunda Sandstone is considered to conformably overlie the Westbourne Formation (Figure 13). However, around the margins of the Surat Basin it is apparently locally disconformable (Green *et al.*, 1997). In GSQ Roma 7 the unit is iron stained and its contact to the underlying Westbourne Formation appears erosional suggesting an unconformity. This agrees with the findings of QGC (2012) who suggest that the boundary is an unconformity. The contact to the

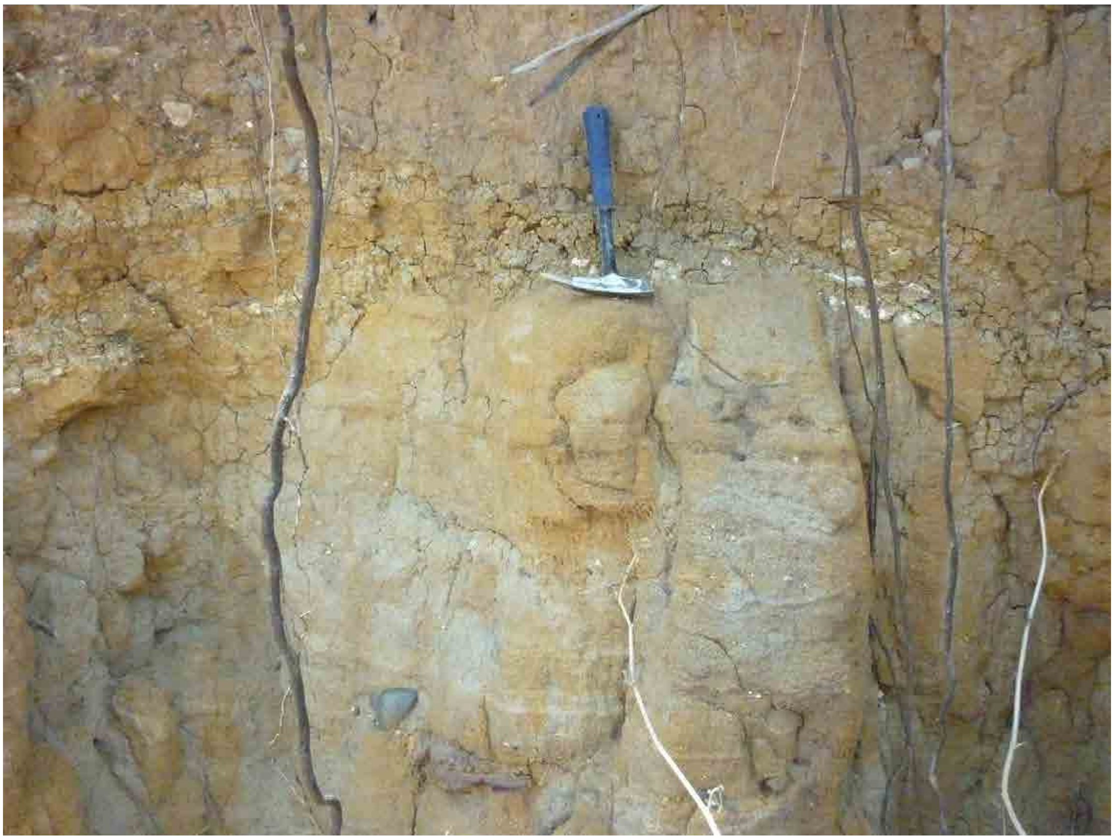


Plate 11: Gubberamunda Sandstone north of Wallumbilla.

underlying Westbourne Formation was not observed in the field. The Gubberamunda Sandstone is overlain by the Orallo Formation. The Gubberamunda Sandstone correlates with the lower section of the Hooray Sandstone in the Eromanga Basin and is recognised as the middle part of the Kumbarilla beds (Green *et al.*, 1997).

Environment of deposition

Day (1964) suggested that the Gubberamunda Sandstone was deposited in a high energy, shallow-water, possibly fluviatile environment. Exon (1976) has noted that the Gubberamunda Sandstone represents the start of the fourth major sedimentary cycle and was deposited by braided and meandering stream systems draining the surrounding highlands. Data from an isopach map in Green *et al.* (1997) suggested that the outlet of the drainage was probably to the south along the axis of the Mimosa Syncline.

Wireline log character

On the resistivity log, the Gubberamunda Sandstone commonly displays a distinctive bell shape with values decreasing in the upper parts, or blocky pattern, reflecting the porous, quartzose nature of the sandstones (Green *et al.*, 1997). The Gubberamunda Sandstone generally has the highest average resistivity log values of all the Surat Basin formations and gamma-ray logs show low average values which commonly increase in the uppermost parts, corresponding to the decrease in values on the bell-shaped resistivity log and a decrease in porosity (Green *et al.*, 1997). The top of the unit is taken where the quartzose sandstones are overlain by the siltstones, shales and sublabile to labile sandstones of the Orallo Formation and this is best seen by the decrease in value in the resistivity log baseline (Green *et al.*, 1997). The boundary with the Orallo Formation is commonly transitional and is difficult to pick if the lowermost Orallo Formation is mostly sandstone (Green *et al.*, 1997).

Hauck & Edwards (Appendix 3, this report) indicate that the Gubberamunda Sandstone typically has a higher average resistivity than the underlying Westbourne Formation which decreases near the top of the unit, and the top is defined as the first occurrence of a low resistivity siltstone at the base of the overlying Orallo Formation. The sonic log is relatively stable with an occasional slight increase in velocity towards the top of the formation. This may be reflecting increased cementation of the upper portion of the formation, or a change to cleaner sandstones. The lower gamma-ray wireline log response reflects the higher sand content contrasting sharply with the lower sand content of the Westbourne Formation.

Thickness

The maximum thickness intersected in the wells within the southern part of the study area of Green *et al.* (1997) was 298 m in UOD Macintyre 1, but it is generally about 100 m thick. The Gubberamunda Sandstone is thinnest around the margins of the basin and thickens towards the southern part of the axis of the Mimosa Syncline (Green *et al.*, 1997). Current QPED data (2015) indicates a maximum thickness of 579.24m in QGC Grace 1 (drilled in 2009) compared with a more representative thickness is 339.86m in QGC Jordan 8 (drilled in 2010).

Age

Palynofloras from the Gubberamunda Sandstone are associated with units APJ62 and APK1 and were considered to be Tithonian–Berriasian (McKellar, 1998), but revision of this age is pending, awaiting the results of zircon isotopic dating from the underlying Westbourne Formation. However, the age of the Gubbermunda Sandstone is presently constrained by the isotopic dating of bentonites in the overlying Orallo Formation, placing the latter formation in the Valanginian (Cooling & McKellar, 2016).

A time break of variable magnitude occurs at the Westbourne Formation–Hooray Sandstone boundary in the Eromanga Basin (Burger, 1986 and 1989; Green & McKellar, 1996a,b, 1998). In its northeastern area, this hiatus is stratigraphically extensive, with the Orallo Formation (Surat Basin) equivalents overlying the Westbourne Formation (McKellar, 1998).

Cover rocks and alluvium

Cover rocks over the Walloon Coal Measures and Springbok Sandstone include Tertiary sediments and lateritic cover, Cainozoic basaltic rocks of the Main Range Volcanics, older alluvium of the Chinchilla Sand, and alluvium and colluvium derived from basaltic rocks that form part of the modern Condamine River system. The distribution of these units is indicated in Appendix 1 which provides a surface geological map at 1:500 000 scale. Geological cross sections illustrate the relationship between the cover sequences and the underlying Mesozoic geology in Cross Sections.

Tertiary sediments

The Tertiary sediments (Ts) are generally thin and quartz-rich and form shallow dipping mesas overlying shallow dipping Mesozoic rocks of the Surat Basin. In the Chinchilla 1:250 000 Map Sheet area large areas of Tertiary sediments were defined by Exon *et al.*, (1968). These authors describe the sediments as comprising a veneer a few metres thick of leached, commonly iron-stained, clayey, fine to coarse grained sandstone with lesser pebbly sandstone and siltstone. This unit covers large areas in the western half of the Chinchilla 1: 250 000 Map Sheet.

Exon *et al.* (1968) have noted scattered surficial cobble layers on the Chinchilla 1:250 000 Map Sheet area that is also evident over the central area of the Taroom 1:250 000 Map Sheet area. Outcrop of these Tertiary sediments near, and on, the OralIo Formation on the Chinchilla 1: 250 000 Map sheet area usually contain a selection of the polymictic pebbles, including fossil wood, reworked from that unit.

The Tertiary sandstones in the Chinchilla 1: 250 000 Map sheet area are quartzose and moderately well-sorted. In most of this area these sediments are very strongly altered and it is considered by Exon *et al.* (1968) that they may have been present when the deep weathering profile was formed. However, this is very difficult to demonstrate conclusively due to lack of exposed vertical outcrop sections. Alternatively, the weathering could be recent and its extensive impact due to high porosity and permeability. There is also the possibility that these fluvial sands were derived from the deep weathering profile and hence have the same character.

In the southwestern corner of the Chinchilla map 1:250 000 Sheet area (Exon *et al.*, 1968) these sands are less weathered but otherwise similar, which tends to support the idea that they are derived from weathered material, as the southwest is downstream and the material has been subjected to more abrasion. The only age control on these sediments is that they are younger than the Lower Cretaceous Wallumbilla Formation (Exon *et al.*, 1968).

Colluvial deposits of the Condamine Basin

The Condamine Basin is herein described as a Cainozoic basin structure developed immediately west of the Main Range and the Bunya Mountains in southeast Queensland. The oldest sediments that have been dated in the basin appear to be Pliocene and have been described as the Chinchilla Sand. There are outcrops of deeply weathered, possibly pre-Oligocene sediments on the western margin of the basin, downstream of the Chinchilla Weir that may represent the earliest fill of the Condamine Basin. The relationship of this outcrop to the subsurface has not been determined but the time of deposition of these sediments and the age of the Coral Sea extension implies that the basin and the sediments are potentially related. The interpreted extent is greater than the current mapped extent on the Chinchilla 1:250 000 Map Sheet by Exon *et al.* 1968.

The radiometric image covering the Condamine Basin allows a method of subdividing the alluvial and colluvial units based on the respective radiometric signatures of surficial deposits on the ternary radiometric image. Comparison with the strata intersected in the water bore logs from each of the units shows some distinct features for each unit. It appears that the oldest colluvial fan and alluvial deposits are represented by the Chinchilla Sand (Tc). This unit is overlain to the north by unit TQf and to the south by unit TQs (formerly mapped as Qs). The latter two units are overlain by unit TQr/b.

From an interpretation of the combined image derived from the ternary radiometrics and digital elevation model data there appears to be several source areas for contribution of sediment to the basin:

Cainozoic basalt of the Main Range Volcanics

These are shown as Tm on accompanying surface geological map (Appendix 1); they are the oldest rocks in the basin that have been dated with an age range from about 30 to 20 Ma (Cranfield *et al.*, 1976; Murphy *et al.*, 1976) and were deposited as a series of alkaline basaltic, trachyitic and rhyolitic flows. The basalt flows predominate and they are characterised on the radiometric image by a red (potassium-rich) signature on the ternary radiometric image and by a normally or reversely polarised image on the magnetic image (Figure 4). The Main Range Volcanics also contain the Cooby Trachyte Member, the areal extent of which has been extended in the current study (through the use of the radiometric and magnetic imagery) to the southeast of its previously mapped extent. The patterns of the magnetic images of the basalt flow indicate they were deposited from multiple vents and flowed along antecedent creek valleys. This formed an originally hard basalt core choking the streams. As the basalt was more resistant to erosion, the interfluves between the streams eroded first. Sediment derived from these interfluve areas were deposited as a series of alluvial fans and stream alluvium. The landscape represented by the basalts show they now form an inverted landscape in which the former creek valleys are now resistant hills. There is also evidence of later alluvium and colluvium covering the basalt flows.

The Main Range Volcanics have a lateral extent from the headwaters of the Condamine River in the south to the Bunya Mountains in the north and locally were deposited to the west in a fault controlled basin (Condamine Basin). The Main Range Volcanics also contain trachyte and rhyolite as separate units and some inter-basalt sediments.

Alluvial fans (colluvium) and alluvium of the Condamine Basin

The oldest of the fluvial / colluvial deposits that have been dated appear to be the Chinchilla Sand which contains a Pliocene vertebrate fauna (Bartholomai and Woods, 1976). The initial alluvial fans of the Condamine Basin were derived from the interfluve areas between the basalt filled valleys with the latest fans derived from weathering of the basalt. Black and red clayey soils moved downslope through sheet wash and solifluxion processes to form the youngest fans—TQr/b. This unit has contributed to the clay-rich basalt-derived surface alluvial deposits of the present Condamine River (Qa/b).

It is assumed that the oldest fan is the Chinchilla Sand. The fans TQf and TQs (an updated symbol from Qs due to its age uncertainty) are locally topographically higher than the Chinchilla Sand. These units may be older or younger than the Chinchilla Sand, but this could not be established in this project.

The northernmost fan, TQf had a primary derivation from the granitic rocks of the Yarraman Subprovince. The TQs fan had a primary derivation from the Mesozoic units and TQr/b is essentially sheet wash from the erosion of weathered basalt.

Existing mapping of the alluvial and colluvial units of the Condamine Basin in the Dalby (Exon *et al.*, 1972), Chinchilla (Exon *et al.*, 1971) and Ipswich 1:250 000 Map Sheets (Cranfield & Swarbrick, 1973) (Figure 19) have recognised most of the fundamental units, but with additional radiometric and DEM imagery and water bore logs these units were able to be interpreted more extensively (Figure 20).

The Chinchilla Sand as mapped by Exon *et al.* (1968) is now interpreted to form a larger dark blue U-rich radiometric area on the ternary radiometric image in the area immediately south of Chinchilla, extending to the south and east of the previously mapped area (Figure 19 and Figure 20).

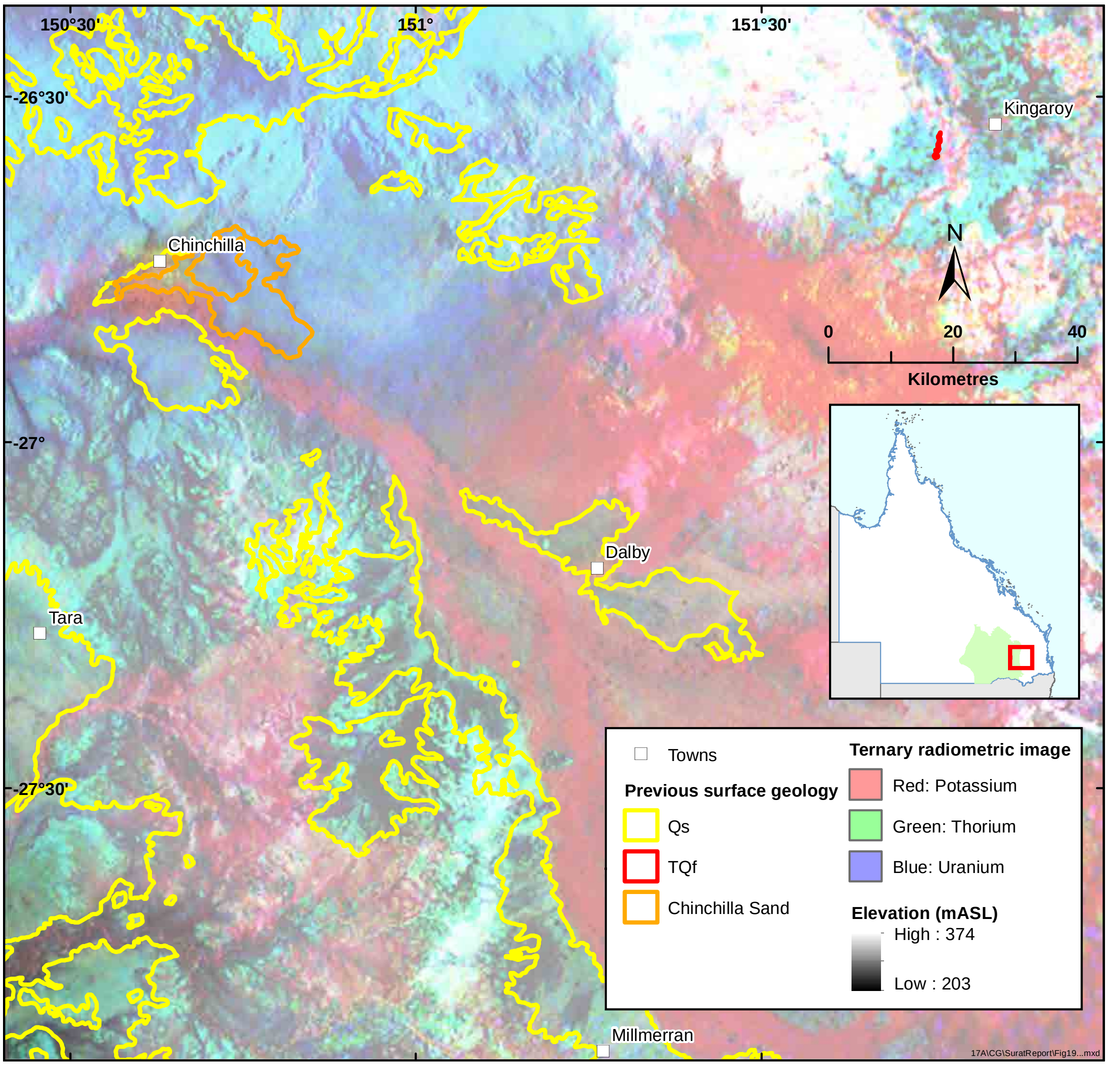


Figure 19. Previous mapping of Cainozoic units in the Condamine Basin.

Alluvial fans

The Chinchilla Sand (Exon *et al.*, 1968) is a thick (~30 m) sequence of interbedded gravel, sand, and clay exposed in many inter-connected gullies and erosional depressions representing multiple episodes of deposition. The sand and clay are typically weakly consolidated, whereas the associated gravel conglomerate is heavily cemented by calcium carbonate. The sediments are most likely derived from the Orallo Formation and associated lateritized soil profiles (Bartholomai & Woods, 1976). Vertebrate fossils from the deposits are referred to as the Chinchilla Local Fauna (Louys & Price, 2013). The Pliocene vertebrate assemblage is represented by at least 63 taxa in 31 families and includes examples of megafauna including Diprotodon. The Chinchilla Local Fauna is Australia's largest, richest and best preserved locality for Pliocene vertebrate fossils, and is eminently suited for palaeoecological and palaeoenvironmental investigations of the late Pliocene (Louys & Price, 2013).

TQs (formerly Qs on the Chinchilla 1:250 000 Map sheet) are dominantly sandy colluvial fans derived from erosion of the targeted Mesozoic units over the central area of the Condamine Basin from the interfluves between the precursor tributary streams for the Condamine Basin that were choked by the basalt. Source rocks for these fans were apparently the sedimentary rocks of the Hutton Sandstone, Marburg Subgroup, Eurombah Formation and Walloon Coal Measures. These areas are recognised by their relief on the DEM and their brownish mottled signature on the radiometric image. It also appears evident that the present Condamine Alluvium (Qa/b) preferentially flows around low remnant hills of these fan materials. Locally TQs is underlain by basalt flows to a depth of 88 m from DNRM

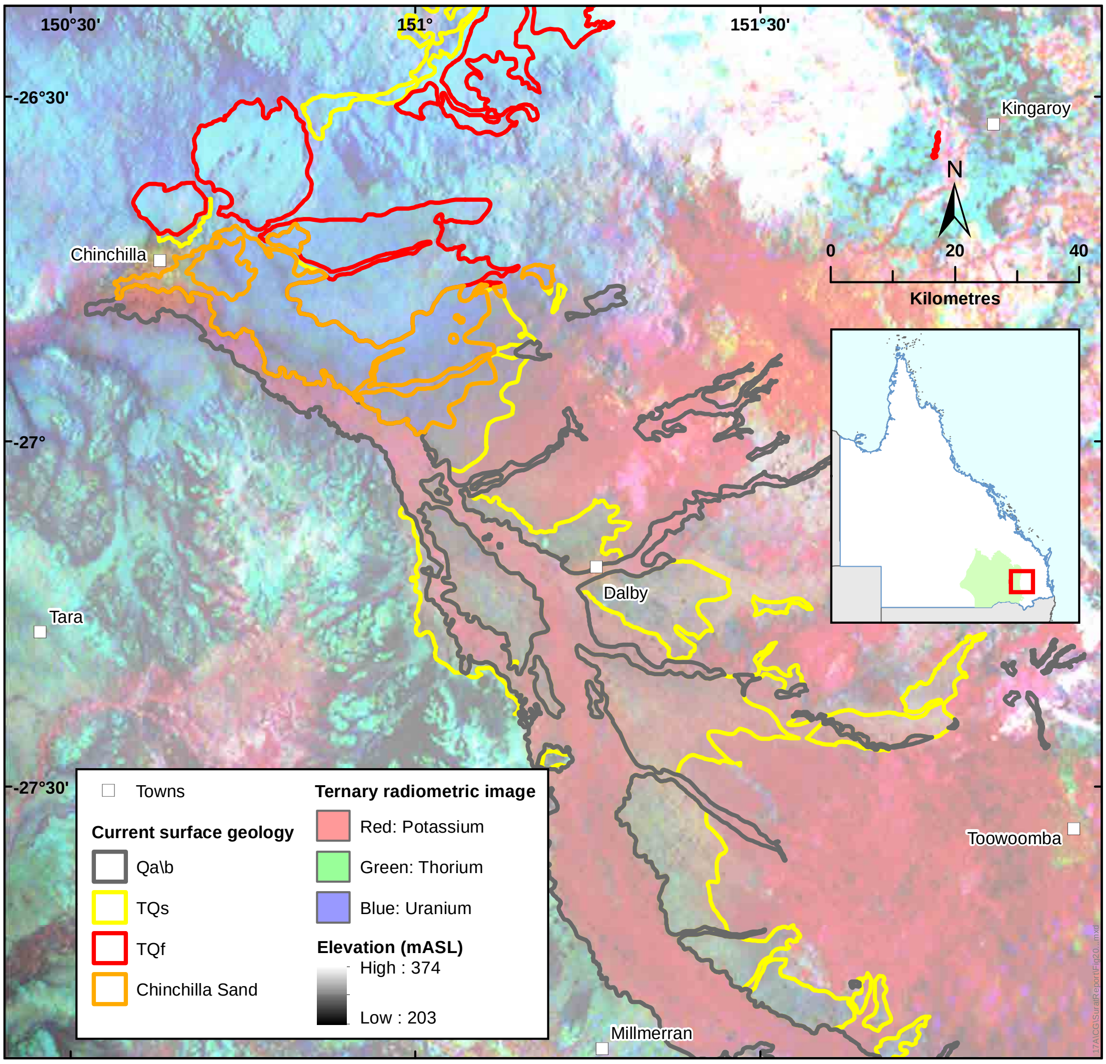


Figure 20. Current mapping showing the changed extent of Cainozoic units.

water bore data. TQf is a colluvial fan and alluvial deposits generated from erosion of the granites and metamorphic rocks of the Yarraman and Auburn Sub provinces to the east with almost no contribution from the Mesozoic sediments. The top of the colluvial fan has a light blue signature indicating the derived sediments are from a source area with a high Th signature. It is the dominant cover type shown as sandy alluvium of the Condamine River based on areal extent in previous mapping by Exon *et al.* (1968).

TQr/b is a colluvial fan derived from erosion and weathering of the Main Range Volcanics. After exposure the basalt weathers to red clay and or a duricrust and black clays. The material is alkali basalt with a significantly high K content as evidenced by the strong red radiometric response on the ternary radiometric image. This unit can be shown to overlie the TQs unit in the central and southern areas of the Condamine Basin and is linked genetically to Qa/b.

Other alluvial sediments

Alluvial units are defined either as Qa (alluvium with no genetically specific link) or Qa/b where there is a genetic link to basaltic source rocks. Unit Qa/b has two major source areas. The southwestern area is sourced from the granites and metamorphic rocks of the Texas Sub province whereas the southeastern branch is sourced from erosion of the Main Range Volcanics. Water bore logs appear to reflect the multiple source contribution to Qa/b with bores showing a clayey top to the alluvium covering a base with a higher sand content.

Collated water bore data and geometry of post-Mesozoic sediments

Leach (2016, in prep) has undertaken a major reassessment of the geometry of the post Mesozoic age sediments as part of a hydrogeological study of the Condamine River Basin, largely informed by a very large number of drilling logs for private and government water bores.

One of the main areas of interest for the mapping project is in the vicinity of the present course of the Condamine River immediately south west of Chinchilla, near the junction with Charleys Creek where seepage of methane through the river bed has been observed.

Structure contours for the base of the post Mesozoic sediment prepared by Leach (2016; in preparation as shown in Figure 5 herein) show some important features related to the structural geology of the Mesozoic age units underlying the Condamine Basin.

Figure 5 shows a clear depocentre at the top of the Mesozoic sequence that is evident in the Formartin – Dalby – Yarrala area. Also evident in Figure 5 are a series of northeast trending linear features which this study has interpreted as faults. The interpretation of these linear features as faults is coupled with the interpretation that they are also magnetic linear features that demonstrably offset features in the basement. Thus, a system of faulting with grabens or half grabens is implied. The geometry of the original extensional basin may have been accentuated by uplift at the southeastern and northwestern margins. In the southeast, substantial uplift associated with the intrusion of the Mount Barney Granophyre (25-20 Ma) has exposed the Carboniferous sediments at the base of the Clarence – Moreton Basin. This uplift may have resulted in a drainage reversal in the antecedent Condamine River and contributed to the development / extent of the alluvial fans derived from the Main Range Volcanics. Vitrinite reflectance data from the Undulla Nose area in the northwest of the Condamine Basin indicates that this area has been uplifted considerably more than adjacent areas. This uplift is consistent with the historical compressional structural regime of eastern Australia. The timing for this uplift is poorly constrained but evidence for fault-related changes in channel morphology is present in the Condamine River, downstream of the Chinchilla Weir implying continued uplift along these structures from the Late Cretaceous to the present.

Such a system has a profound impact on the methodology required to be employed for the current study to map the subcrop extent of the Springbok Sandstone, Walloon Coal Measures and Eurombah Formation below the Condamine Basin sediments. Initially, it was hoped that the position of the subcrop boundaries beneath the Condamine Basin sediments could be achieved via revision and extension of available structure elevation contours for the tops of these formations. This was to be coupled with a subsurface projection to intercept the elevation contours for the base of the Condamine Basin sediments (i.e. the erosional surface on the top of the Mesozoic sequence). Because of the presence of likely block faulting as demonstrated by the work of Leach (2016, in prep) this approach was discarded.

Alternative approaches were then trialled to define the subcrop extents of Springbok Sandstone, Walloon Coal Measures and Eurombah Formation beneath the Condamine Basin cover material. The water bore databases compiled for Leach's (2016, in prep) work were freely made available to the project team and one of the attributes was an interpretation of the stratigraphy of the Mesozoic sequences intercepted by water bores. Initial subcrop boundary mapping was undertaken using water bore data, some selected coal exploration borehole data and the digital elevation model. The results of this mapping were deemed unreliable (e.g. subcrop patterns that could not be reconciled with likely structural features).

A more detailed consideration of coal exploration borehole data recently compiled by QGC was required, together with further consideration of stratigraphy defined in available coal seam gas appraisal/ exploration and development wells, other petroleum wells and stratigraphic bores. The process was somewhat iterative in that for many CSG wells, reliable identification of stratigraphy was not always available for the upper sections of the wells above the coal seam production areas. Recourse back to the elevation contours of the base of the Condamine Basin / top of the Mesozoic sequence was required to determine the likely uppermost Mesozoic age formation in subcrop beneath the Condamine Basin.

Cross sections

Six cross sections were created across the project area to confirm and visualise the mapping of the surface geology to the subsurface determined from boreholes. In the cross sections, regions designated as cover include: Tertiary sediments; duricrust in zones of deep weathering; alluvium and colluvium; sediments and volcanics of the Main Range Volcanics. The cover on each section is designated on the profile. The source data column for each section shows the origin of the data used for the generation of the cross sections. The comment 'Supplied by Origin for Project' shows where this data was not readily accessible on QDEX, but may be open file information.

Section AB (Meeleebee)

Section AB (Table 2) is focused through the type area of the Eurombah Formation along the axis of the Eurombah Dome. The section also shows the variation of the thickness of the Eurombah Formation as it plunges to the south into the basin. The variations in thickness of the Springbok Sandstone from borehole data express the unconformity between the Springbok Sandstone and the underlying Walloon Coal Measures. The borehole data supports the interpretation of the extent and thickness of the target units in this area.

Table 2. Summary of borehole data use in section AB

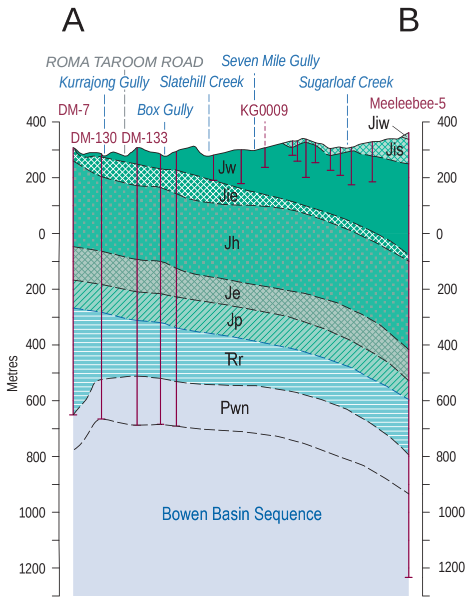
Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Origin Energy Resources	OEL	DM-7	NA	ATP592 (CR 33123)
Australia Pacific LNG Ltd	AUS	DM-130 DM-133	NA	ATP592 Supplied by Origin for Project
Australia Pacific LNG Ltd	AUS	DM-176	NA	ATP592 Supplied by Origin for Project
Australia Pacific LNG Ltd	AUS	DM-180	NA	ATP592 - Supplied by Origin for Project
Australia Pacific LNG Ltd	AUS	RN14390	29762 Dundonnell 4	DNRM – GWDB
Australia Pacific LNG Ltd	AUS	RN14391	30031 Limewood Bore	DNRM – GWDB
Mines Administration	MAD	KG0009	NA	ATP 56 (CR 928)
Thiess Brothers	TPM	R0015	NA	EPC114
Mines Administration	MAD	KG0007	NA	ATP 56 (CR 928)
Marathon Petroleum Australia	MPA	SF0011	NA	EPC 399 (CR 11821)
Mines Administration	MAD	KG0004	NA	ATP 56 (CR 928)
Marathon Petroleum Australia	MPA	SL029	NA	EPC 410 (CR 12614)
Mines Administration	MAD	KG002R	NA	ATP 56 (CR 928)
Marathon Petroleum Australia	MPA	ORO-106	NA	Supplied by Origin for Project
Marathon Petroleum Australia	MPA	ORO-098	NA	Supplied by Origin for Project
Australia Pacific LNG Ltd	AUS	Meeleebee-5	NA	Supplied by Origin for Project

NA= Not available; DM= Durham Ranch; RN=DNRM water bore registered number;
DNRM-GWD= Department of Natural Resources and Mines, Groundwater database; KG =Kooringa

MEELEEBEE

Cenozoic units omitted

$\frac{V}{H} = 20$



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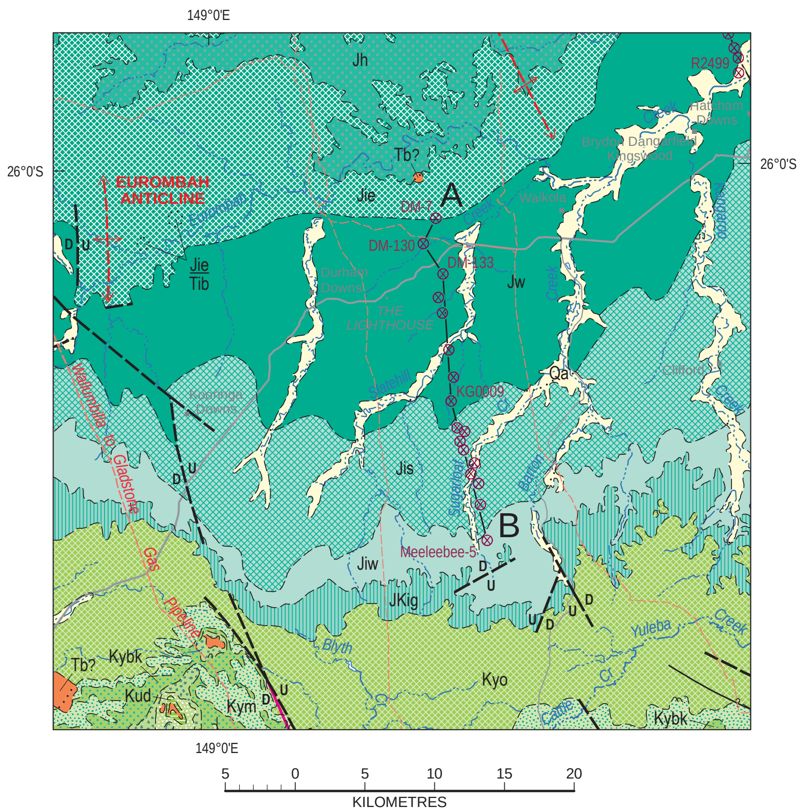
Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
DM-7	958.29	RN14391	121.90	SL029	78.00
DM-130	950.70	KG0009	70.00	KG002R	100.00
DM-133	996.20	R0015	51.83	ORO-106	138.00
DM-176	985.70	KG0007	73.00	ORO-098	144.00
DM-180	985.70	SF0011	138.00	Meeleebee-5	1595.30
RN14390	91.40	KG0004	72.00		

Depth in metres.

Jiw—Westbourne Formation, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Je—Evergreen Formation, Jp—Precipice Sandstone Bowen Basin Sequence; Rr—Rewan Group, Pwn—Bandanna Formation



Section CD (Norwood)

This is a north–south section (Table 3) across a thicker section of the Eurombah Formation on the western limb of the Mimosa Syncline. The section generally dips and thickens to the south into the southerly plunging axis of the syncline. Changes in the depth of intersection of the Eurombah Formation at the southern end of the section indicate minor normal faulting from borehole intersections. This apparently is linked to south-block-down movements on an interpreted basement fault close to the southern extent of the section line.

Table 3. Summary of borehole data use in section CD.

Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Department of Natural Resources and Mines	DNRM	RN13238	30184	DNRM – GWDB
Department of Natural Resources and Mines	DNRM	RN15960	30161 Moleskin Creek	DNRM – GWDB
Department of Natural Resources and Mines	DNRM	RN12446	30183 Utopia Downs	DNRM – GWDB
Exoil- Petromin		HB0025	NA	Supplied by Origin for Project
Department of Natural Resources and Mines	DNRM	RN16385	30177 Fred's bore	DNRM – GWDB
Department of Natural Resources and Mines	DNRM	RN58296	Amusen's bore	DNRM – GWDB
Thiess	TPM	RO431	NA	Supplied by Origin for Project
Thiess	TPM	R1963	NA	Supplied by Origin for Project
Thiess	TPM	R430	NA	Supplied by Origin for Project
Thiess	TPM	R336	NA	Supplied by Origin for Project
Thiess	TPM	R337	NA	Supplied by Origin for Project
Thiess	TPM	R338	NA	Supplied by Origin for Project
Department of Natural Resources and Mines	DNRM	RN48977	Bore no. 2	DNRM – GWDB
Thiess	TPM	R2499	16333 Yackadoo	Supplied by Origin for Project
Thiess	TPM	R2498	16328 Dunbar	Supplied by Origin for Project
Department of Natural Resources and Mines	DNRM	RN48979	Bore no. 1	DNRM – GWDB
Department of Natural Resources and Mines	DNRM	13030812	NA	DNRM – GWDB
NA	NA	TM165	NA	Supplied by Origin for Project
Marathon Petroleum Australia Ltd	MPA	EU93	NA	Supplied by Origin for Project
Marathon Petroleum Australia Ltd	MPA	EU79	NA	Supplied by Origin for Project
Department of Natural Resources and Mines	DNRM	RN17005	29867 Tangalooma	DNRM – GWDB
Thiess	TPM	R208	NA	EPC139
Queensland Gas Company Ltd	QGC	Thackery 3	NA	ATP 852 (CR73366)

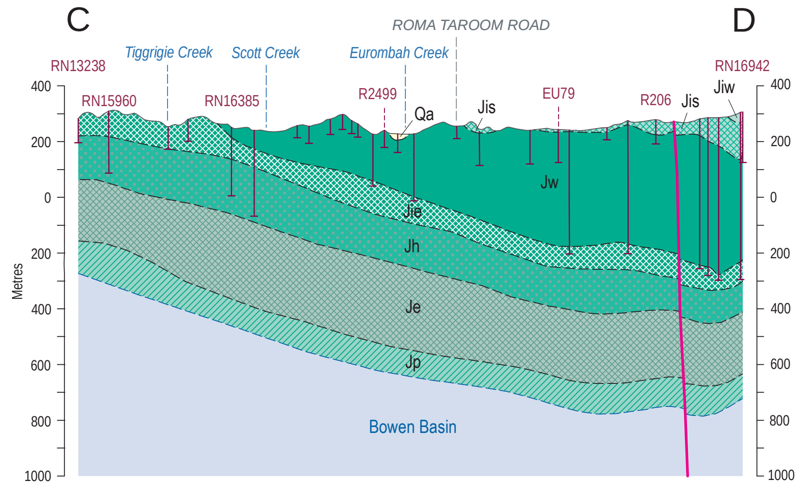
Table 3 (continued).

Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Thiess Brothers	TPM	R206	NA	EPC139
Origin Energy Resources	OER	COM-NTH-11	NA	Supplied by Origin for Project
Origin Energy Resources	OER	COM-NTH-21	NA	Supplied by Origin for Project
Origin Energy Resources	OER	COM-NTH-30	NA	Supplied by Origin for Project
Origin Energy Resources	OER	COM-NTH-49	NA	Supplied by Origin for Project
Origin Energy Resources	OER	RN16942	Norwood 8	DNRM – GWDB

NA= Not applicable; DM= Durham Ranch; RN=DNRM water bore registered number; COM= Combabula; NTH=North; CR = QDEX company report number; DNRM-GWD = DNRM groundwater database

NORWOOD

V/H = 20



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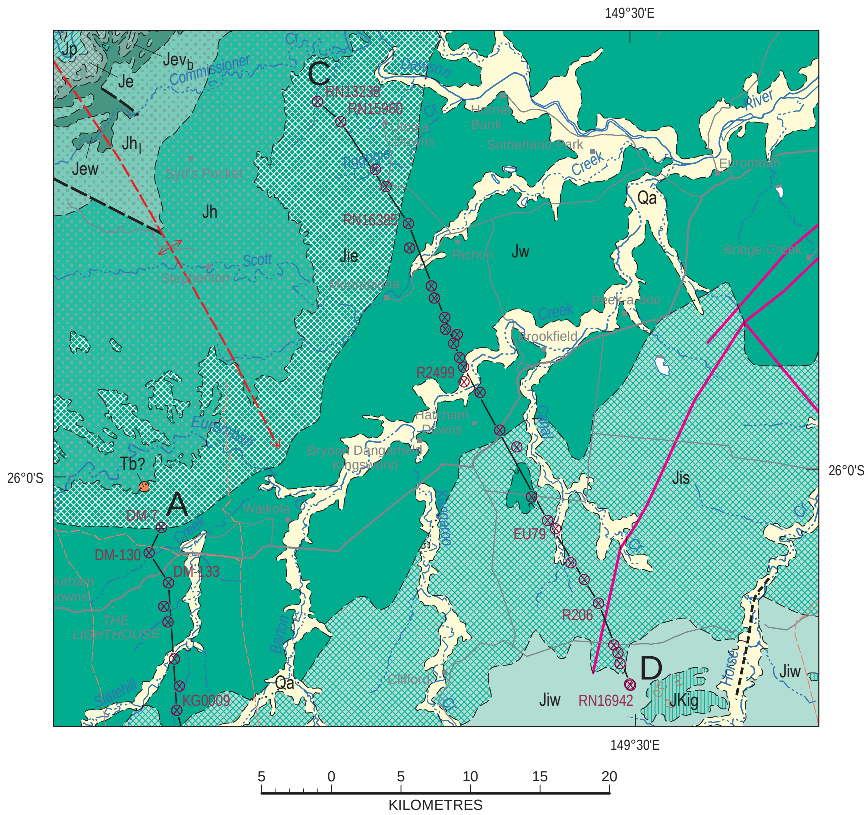
Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
RN13238	85.95	R337	47.32	RN17005	442.57
RN15960	219.45	R338	47.32	R208	42.68
RN12446	80.77	RN48977	185.93	Thackery-3	477.03
HB0025	76.20	R2499	60.00	R206	88.43
RN16385	243.84	R2498	66.00	COM-NTH-11	535.00
RN58296	304.80	RN48979	239.27	COM-NTH-21	566.00
RO431	42.74	13030812	42.60	COM-NTH-30	583.50
R1963	60.00	TM165	120.00	COM-NTH-49	600.00
R430	56.48	EU93	120.00	RN16942	177.80
R336	51.90	EU79	120.00		

Depth in metres.

Qa—Quaternary alluvium, Jiw—Westbourne Formation, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Je—Evergreen Formation, Jp—Precipice Sandstone



Section EF (Sandpit)

Section EF (Table 4) is in the outcrop area on the Taroom 1:250 000 Map Sheet. It is essentially a southwest–northeast section through the whole of the targeted section from the Eurombah Formation through to the base of the Westbourne Formation which includes the main target units: the Eurombah Formation, Walloon Coal Measures and the Springbok Sandstone. Significant changes in depth from borehole intersections of Eurombah Formation occur in the vicinity of a faulted area. These variations indicate late reverse movements on this fault. This is in agreement with a regionally extensive current seismic project interpreting the style of Cainozoic fault movements derived from interpretation of the seismic coverage in the basin (Jeff Copley, Centre for Coal Seam Gas Research, University of Queensland, personal communication, 2016). Similar movements are proposed for all the Surat Basin units in the area.

Table 4. Summary of borehole data use in section EF.

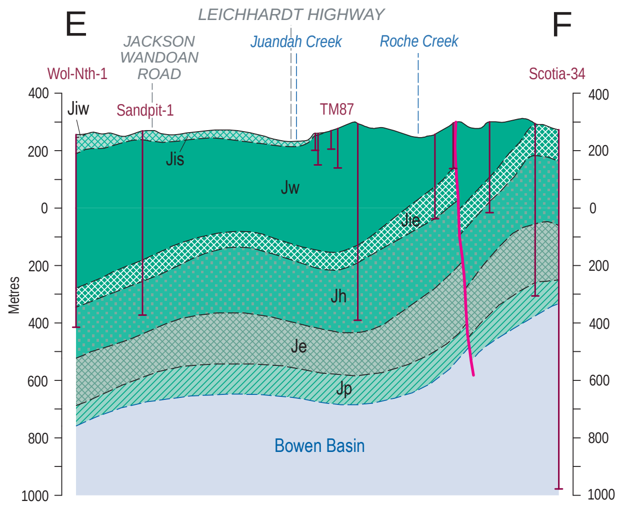
Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Australia pacific LNG Ltd	AUS	Wol-Nth-1	NA	ATP 692 Supplied by Origin for project
Australia pacific LNG Ltd	AUS	Sandpit-1	64162	ATP 606 (CR 71938)
NA	NA	TU115	NA	Supplied by Origin for project
Marathon Petroleum Australia Ltd?	MPA	TE26	NA	Supplied by Origin for project
NA	NA	TU125	NA	Supplied by Origin for project
Marathon Petroleum Australia Ltd	MPA	TM87	NA	Supplied by Origin for project
Department of Natural Resources and Mines	DNRM	RN58377	Playfair Group Bore	DNRM – GWD
Geological Survey of Queensland	GSQ	GSQ ROMA 1	NA	Supplied by Origin for project
NA	NA	BK171	NA	Supplied by Origin for project
Department of Natural Resources and Mines	DNRM	RN16661	Twin butts No.	DNRM – GWD
Department of Natural Resources and Mines	DNRM	RN154987	32517	DNRM – GWD
Santos	SSL	Scotia-34	64243	PL 176 (CR 6780)

Wol=Woleebee; NTH=North; NA=not applicable; CR = QDEX company report number;
DNRM-GWD = DNRM groundwater database; RN=DNRM water bore registered number.

SANDPIT

Cenozoic units omitted

$\frac{V}{H} = 20$

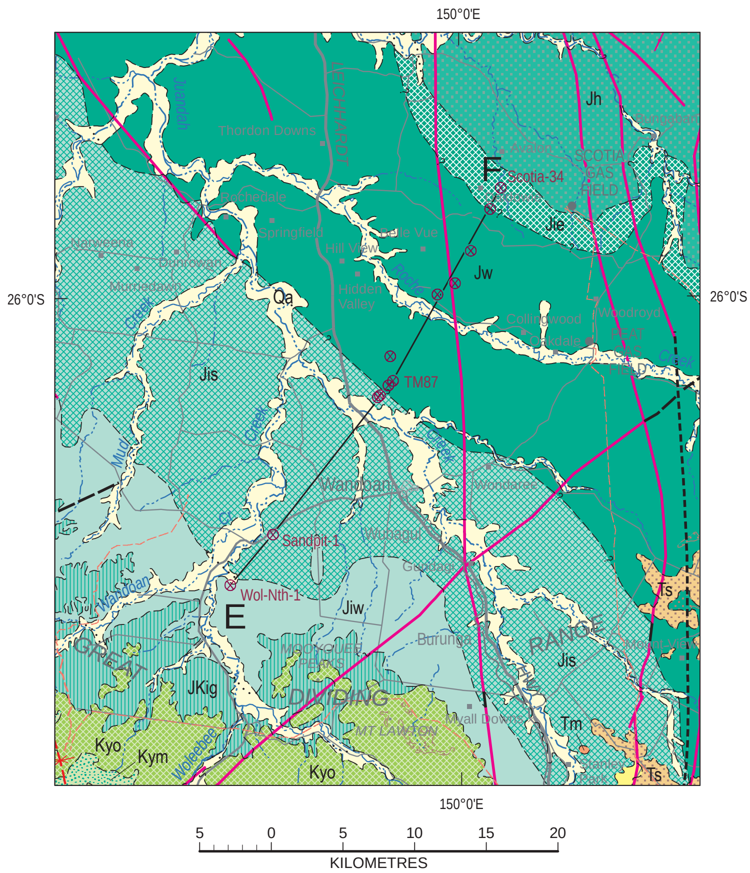


INDEX TO BOREHOLES

Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
Wol-Nth-1	671.20	TU125	64.00	BK171	163.00
Sandpit-1	641.20	TM87	138.00	RN16661	316.38
TU115	60.00	RN58377	686.00	RN15487	599.24
TE26	110.00	GSQ Roma 1	293.80	Scotia-34	1251.50

Depth in metres.

Jiw—Westbourne Formation, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Je—Evergreen Formation, Jp—Precipice Sandstone



Section GH (Chinchilla)

Section GH (Table 5) forms an southwest–northeast profile across the northern part of the Cainozoic Condamine Basin where the Mesozoic targeted units are covered by consolidated sedimentary rocks and locally basalt, unconsolidated alluvial and colluvial sediments up to 100 m thick. This area also includes the methane seeps of the Condamine River system. The Springbok Sandstone is locally exposed on the banks of Charley Creek (Plate 12) where it contains fossil wood (Plate 13) and is locally deeply weathered with a well-developed lateritic surface (Plate 14).

Table 5. Summary of borehole data use in section GH.

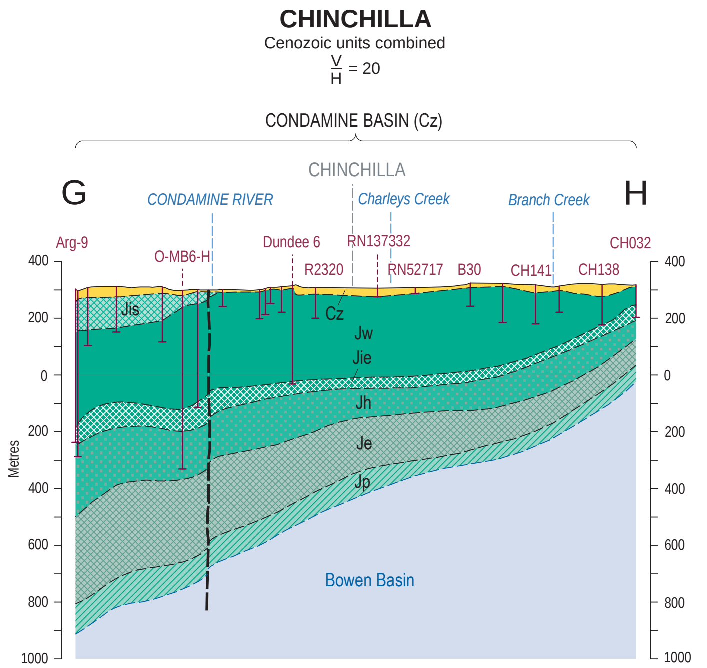
Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Queensland Gas Company Ltd	QGC	Arg-9	NA	ATP 320 (CR38844) (Argyle 9)
Queensland Gas Company Ltd	QGC	Arg-136	NA	ATP320 (Argyle 136) Supplied by Origin for project
NA	NA	ML 35	NA	Supplied by Origin for project
Department of Natural Resources and Mines	DNRM	RN8665	33552	DNRM – GWD
Department of Natural Resources and Mines	DNRM	RN5390	33454	DNRM – GWD
Origin Energy Ltd	OEL	O-MB6-H	NA	ATP 215
Australia Pacific LNG Pty Ltd	AUS	O-MB5-W	NA	EPC562 Supplied by Origin for project
Thiess Brothers	TPM	CO100	NA	EPC 431(CR 19226)
AMH (Chinchilla Coal) Pty Ltd	AMH?	CH05	NA	EPC 562 Supplied by Origin for project
AMH (Chinchilla Coal) Pty Ltd	AMH?	R005A	NA	EPC 562 Supplied by Origin for project
AMH (Chinchilla Coal) Pty Ltd	AMH?	R2222	NA	EPC 562 Supplied by Origin for project
AMH (Chinchilla Coal) Pty Ltd	AMH?	CH07	NA	EPC 562 Supplied by Origin for project
Arrow Energy Ltd	AEL	Dundee 6	NA	ATP676 (CR64270)
CSR Coal Division	CSR	R2320	NA	EPC431- Supplied by Origin for project
Department of Natural Resources and Mines	DNRM	RN137332	NA	DNRM – GWD
Department of Natural Resources and Mines	DNRM	RN52717	NA	DNRM – GWD
Baracluith Pty Ltd	NA	B30	NA	NA
Marathon Petroleum Australia	MPA	CH296	NA	CR 13463
Marathon Petroleum Australia	MPA	CH141	NA	Supplied by Origin for project
Baracluith	NA	B28	NA	Supplied by Origin for project
Marathon Petroleum Australia	MPA	CH138	NA	EPC 255 (CR 10700)
Marathon Petroleum Australia	MPA	CH032	NA	EPC 255 (CR 10700)

O = Orana; OMB = Origin Energy, NA = Not applicable; DNRM-GWD = DNRM groundwater database; RN = DNRM water bore registered number.

Plate 12: Springbok Sandstone along Charley Creek, approximately 10 km south of Chinchilla.

Plate 13: Fossil wood in Springbok Sandstone.

Plate 14: Lateritised pebble conglomerate in Springbok Sandstone.

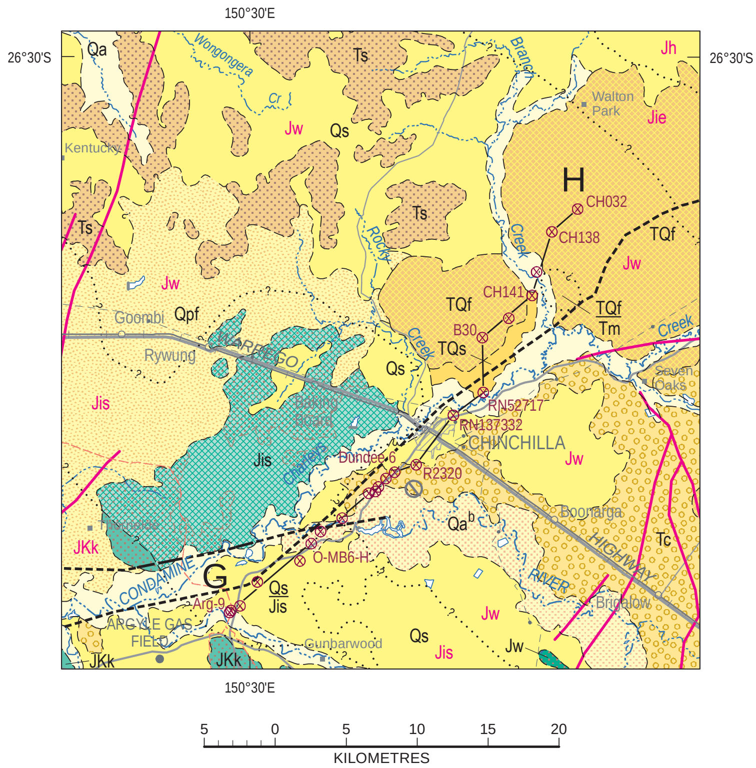


INDEX TO BOREHOLES

Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
Arg-9	540.00	CH05	102.00	B30	91.44
Arg-136	585.00	R005A	91.86	CH296	138.00
ML 35	204.00	R2222	53.00	CH141	138.00
RN8665	160.60	CH07	90.00	B28	94.48
RN5390	193.50	Dundee 6	345.19	CH138	138.00
O-MB6-H	630.00	R2320	108.00	CH032	115.15
O-MB5-W	415.00	RN137332	30.50		
CO100	60.31	RN52717	21.00		

Depth in metres.

Cz—Cenozoic cover, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Je—Evergreen Formation, Jp—Precipice Sandstone



Section IJ (Macalister)

Section IJ (Table 6) is a southwest–northeast section south of GH and shows significant changes in the thickness of the Westbourne Formation and Springbok Sandstone at the western end of the section. This may be due to down cutting of the Springbok Sandstone into the underlying Walloon Coal Measures accompanied by the development of local normal growth faults at the edge of the basin. The Westbourne Formation (part of the undifferentiated Kumbarilla beds in this region) occurs in borehole David 123 but is not represented in borehole Daandine 27T indicating a fault between these bores. This section, and Section GH to the north and section KL (Tipton) to the south, are areas of subcrop of the Marburg Subgroup. Mostly, the units of the Surat Basin are defined in the subsurface to the west and a facies boundary is shown on the accompanying section. In reality, the Marburg Subgroup is essentially equivalent to the combined Hutton Sandstone and Evergreen Formation in this area.

Table 6. Summary of borehole data used in section IJ.

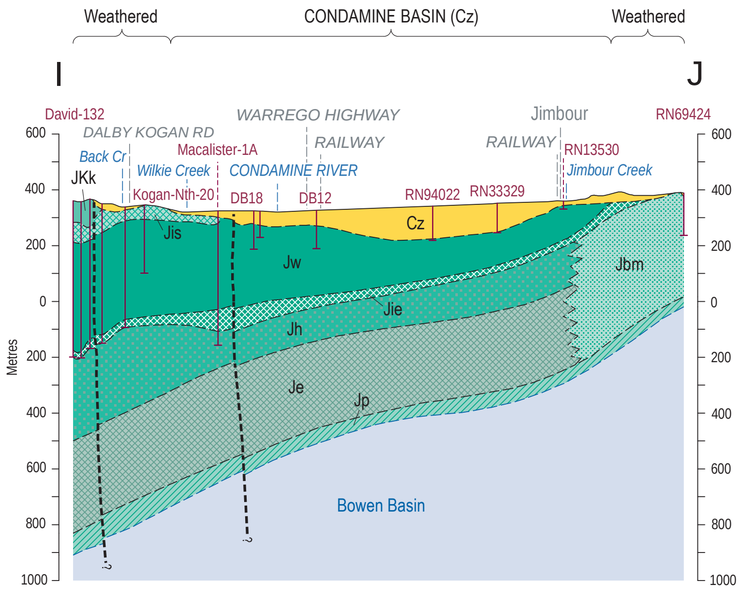
Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Queensland Gas Company Pty Ltd	QGC	David-132	NA	Supplied by Origin for project
Queensland Gas Company Pty Ltd	QGC	David-122	NA	Supplied by Origin for project
Queensland Gas Company Pty Ltd	QGC	David-123	NA	Supplied by Origin for project
Arrow Energy Ltd	AEL	Daandine-27T	NA	ATP230 (CR 62213)
Arrow Energy Ltd	AEL	Daandine-18T	NA	ATP 230 (CR61300)
Arrow Energy North NL	AEL	Kogan-Nth-20	NA	CR43246
Arrow Energy Ltd	AEL	Macalister 1A	NA	
Marathon Petroleum Australia Ltd	MAP	DB18	NA	Supplied by Origin for project
DNRM	DNRM	RN18151	NA	(DNRM-GWDB)
Marathon Petroleum Australia Ltd	MAP	DB12	NA	Supplied by Origin for project
DNRM	DNRM	RN94022	NA	DNRM-GWD
DNRM	DNRM	RN33329	NA	DNRM-GWD
DNRM	DNRM	RN13530	NA	DNRM-GWD
DNRM	DNRM	RN69424	NA	DNRM-GWD

NA= Not applicable; DNRM-GWD = Department of Natural Resources and Mines groundwater database; RN=DNRM water bore registered number.

MACALISTER

Cenozoic units combined

V/H = 20



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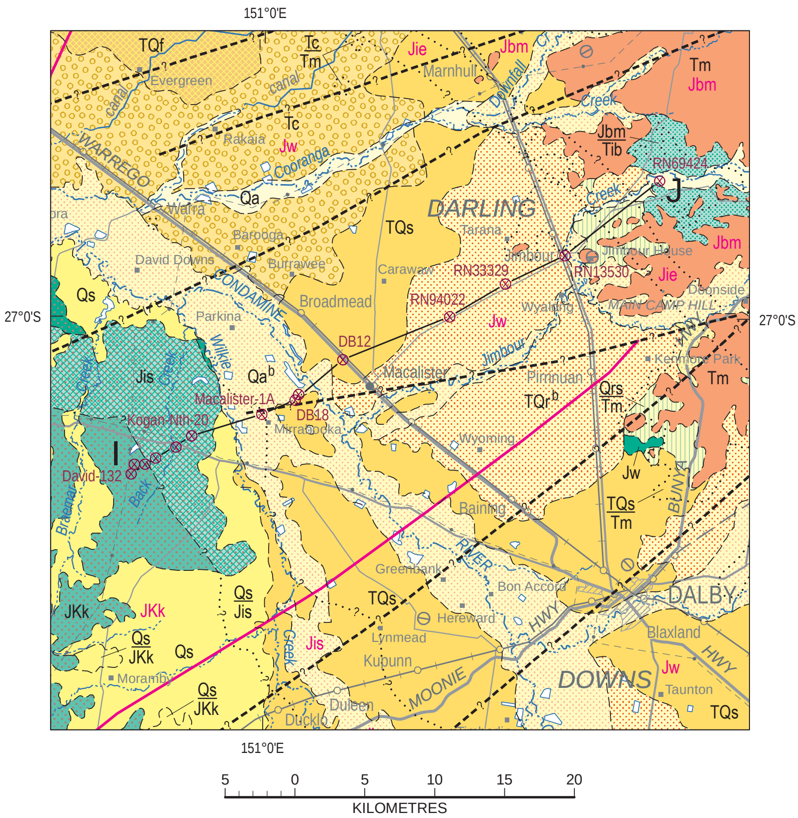
Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
David-132	560.29	Kogan-Nth-20	245.99	RN94022	121.92
David-122	560.00	Macalister-1A	481.00	RN33329	105.92
David-123	534.77	DB18	138.00	RN13530	28.00
Daandine-27T	500.00	RN18151	94.48	RN69424	151.00
Daandine-18T	431.24	DB12	138.00		

Depth in metres.

Cz—Cenozoic cover, JKk—Kumbarilla beds, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Jbm—Marburg Subgroup, Je—Evergreen Formation, Jp—Precipice Sandstone



Section KL (Tipton west)

Cross Section KL (Table 7) shows the thinning of the target formations as they approach their subcrop and the thickness of Cenozoic cover in the region of this section. Changes in the base of the Springbok Sandstone are due to its extensive local down cutting into the Walloon Coal measures. This section also shows local down cutting of the Gubberamunda Sandstone into the underlying Westbourne Formation. The greater thickness of the Walloon Coal Measures may be due to local subsidence caused by local normal faulting during deposition. There may also be some reverse faulting associated with latest Cainozoic deformation in the basin, close to the western end of the section. Some of the well logs in this section were reinterpreted by Origin Energy and this is reflected in the changes of the boundary between the Westbourne Formation and the Gubberamunda Sandstone. All the formations appear to thin towards the outcrop area.

Table 7. Summary of borehole data use in section KL.

Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Queensland Gas Company	QGC	Harry-217	69647	ATP 279 - data supplied by origin for project
Queensland Gas Company	QGC	Harry-218	71258	ATP 279 -data supplied by origin for project
Queensland Gas Company	QGC	Harry-219	71257	ATP 279- Supplied by Origin for project
Queensland Gas Company	QGC	Harry-210	71260	ATP 279- data supplied by origin for project
Queensland Gas Company	QGC	Harry-201	67772	ATP 279 -data supplied by origin for project
Arrow Energy NL	AEN	Tipton-44T	61408	ATP 198 (CR 56634)
Arrow Energy NL	AEN	Tipton-50	59851	ATP 198 (CR 50670)
Arrow Energy NL	AEN	Tipton-38T	61406	ATP 198 CR 56933
Arrow Energy NL	AEN	Tipton-31	59797	ATP 198(CR 5064)
Marathon petroleum Australia	MPA	TP8	NA	EPC 280 (CR 11823)
Marathon petroleum Australia	MPA	TP21	NA	EPC 280 (CR 11823)
Department of Natural Resources and Mines	DNRM	RN42230148	NA	DNRM-GWD West- West End Line
Department of Natural Resources and Mines	DNRM	RN107238	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN147124	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN147119	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN119127	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN18913	NA	DNRM-GWD

Table 7 (continued).

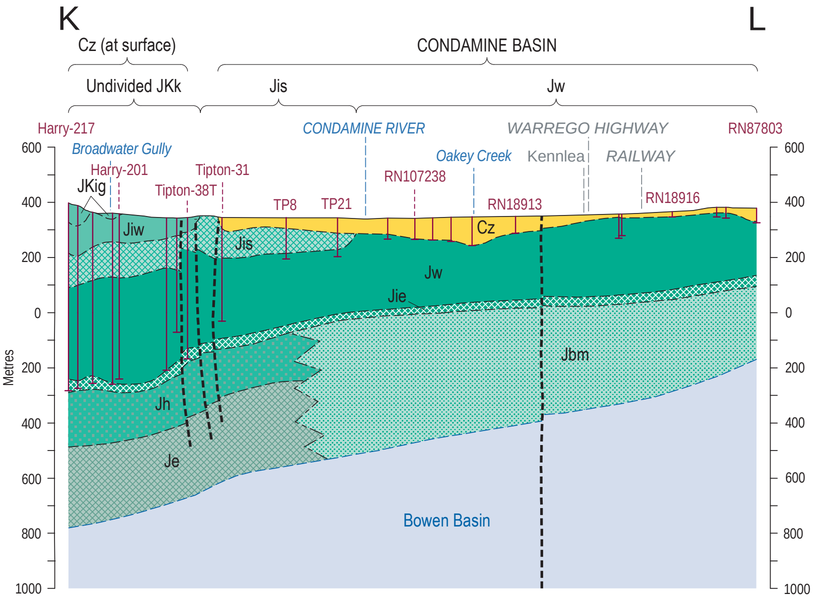
Company name	Company designation	Borehole on section	MERLIN borehole # if available (generally prior to 1988)	Source data (QDEX, groundwater database)
Department of Natural Resources and Mines	DNRM	RN147377	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN48018	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN18916	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN19009	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN19011	NA	DNRM-GWD
Department of Natural Resources and Mines	DNRM	RN87803	NA	DNRM-GWD

NA = Not available; DNRM-GWD = DNRM groundwater database;
RN = DNRM water bore registered number.

TIPTON WEST

Cenozoic units combined

$\frac{V}{H} = 20$

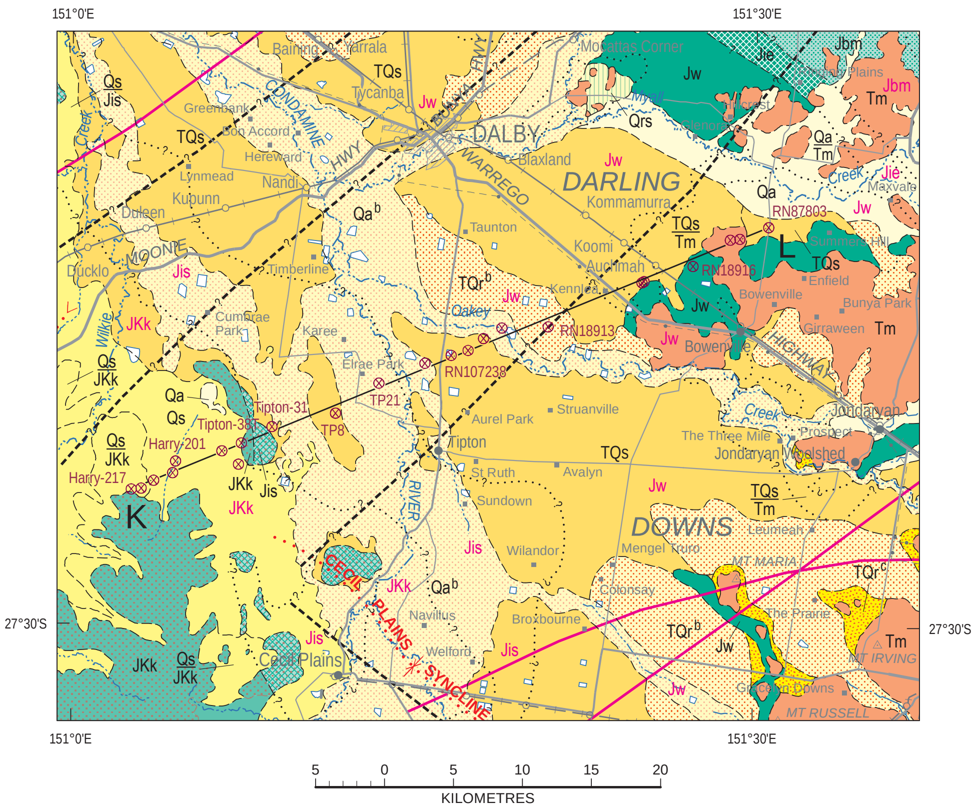


INDEX TO BOREHOLES

Hole Name	Total Depth	Hole Name	Total Depth	Hole Name	Total Depth
Harry-217	680.00	Tipton-31	375.00	RN18913	61.57
Harry-218	665.00	TP8	150.00	RN147377	88.00
Harry-219	625.00	TP21	141.00	RN48018	79.20
Harry-210	620.40	RN42230148	76.20	RN18916	18.90
Harry-201	599.90	RN107238	76.20	RN19009	35.00
Tipton-44T	552.47	RN147124	80.20	RN19011	39.00
Tipton-50	420.66	RN147119	87.80	RN87803	53.20
Tipton-38T	511.99	RN119127	105.00		

Depth in metres.

Cz—Cenozoic cover, JKk—Kumbarilla beds, JKig—Gubberamunda Sandstone, Jiw—Westbourne Formation, Jis—Springbok Sandstone, Jw—Walloon Coal Measures, Jie—Eurombah Formation, Jh—Hutton Formation, Je—Evergreen Formation, Jbm—Marburg Subgroup



Conclusions

Two new maps (and digital data packages) have been created which substantially improve the knowledge of the location of the targeted CSG producing formations of the basin.

The outputs in Phase 1 of the project showed the value of developing an initial framework for the location of alluvium, colluvium and basalt overlying the target formations. Phase 1 developed a method for defining the whole of the section from the top of the Hutton Sandstone / Marburg Subgroup to the base of the Westbourne Formation in the outcrop area in the Taroom and Roma 1:250 000 Map Sheet areas. The mapping of the targeted formations for the project, particularly in Phase 2 has identified surface outcrop of the Eurombah Formation, Walloon Coal Measures and Springbok Sandstone. These boundaries were field checked at the end of Phase 2 in conjunction with a validation of the interpretation using detailed borehole logs from CSG wells.

This definition of the outcrop area has been generated from the interactive use of multiple data sets in combination with the existing geological mapping and borehole data. The subsurface extent of these units has been generated from a combination of image interpretation and the use of data from a range of borehole types, including stratigraphic, water, coal exploration, coal seam gas wells and historical petroleum wells. The major issue in creating a map of the target formations has been inconsistencies in the definition of stratigraphy between different data sources.

The most effective tools for the project have been the remotely sensed data for identifying the following characteristics of the key formations:

1. Aerial photography: This was used mainly to identify additional areas of alluvium and colluvium that were not compiled in the original mapping. Interpretation of these areas was undertaken to be consistent with the size of areas interpreted in the original mapping using 1:85 000 scale aerial photography locally in conjunction with the radiometric imagery and the DEM.
2. Radiometric data (including the ternary image and the individual channels) greatly assisted in the following interpretations:
    a. The top of the Hutton Sandstone (in the Taroom and Roma 1:250 000 Map Sheets) was identified by its high radiometric response in the K and Th channels and by its more resistant topography reflected in the DEM. Variations within the Hutton Sandstone on the western limb of the Mimosa Syncline and the occurrence of the Boxvale Sandstone Member on the eastern limb of the Mimosa Syncline were identified using this method.
    b. The top of the Springbok Sandstone (base of Westbourne Formation) was identified by its significantly higher Th response and high K and its more subdued topography on the DEM in the outcrop area. A wide range of borehole data was used to define this boundary under cover to the south.
    c. Combining the known location of coal mines on the SPOT satellite image data and on the DEM with resource polygons from GSQ data and coal relinquishment reports has assisted with defining the top of the Walloon Coal Measures and the Springbok Sandstone unconformity at the top of the Walloon Coal Measures.
    d. The Springbok Sandstone base in the outcrop area is distinguished by its higher K signature than from the underlying Walloon Coal Measures, as well as its more resistant topography on the DEM.
    e. Combining the radiometric response and the DEM shows the variations in source areas for the alluvial fans and alluvial deposits of the Condamine Basin and locally, the Dawson River tributary system.
3. Magnetic and DEM data assisted in generating a fault array that explained the spatial configuration of geological units in the project area. Linking the fault array to the water bore data has assisted the interpretation of basement faults that may have had Cainozoic movement creating

the ‘Condamine Basin’ and offsetting Mesozoic units in the subsurface. Interpretation of the Cainozoic volcanics using the magnetic data showed that most flows of magma were along creek lines and that there were both normally and reversely polarised flows indicating age differences in the flows. The magnetic signature indicates there is basalt at depth in areas where there are Mesozoic rocks at surface. This indicates the presence of sills in the subsurface in these regions and this has been shown as Tib on the accompanying surface geology map.

4. Analysis of the water bore data showed the extent of units of the ‘Condamine Basin’ in the subsurface and gave some indication of the relative age of the constituent units. The Chinchilla Sand is apparently the oldest sedimentary unit that has been dated and TQr/b, Qa/b and Qa are the youngest. The ages of TQf and TQs are unknown, but TQf is considered older as it may have been eroding the granite bodies of the Yarraman Subprovince prior to the extrusion of the Cainozoic volcanics.
5. Definition of the base of the Walloon Coal Measures under the Condamine Basin is problematic. Some of the water bore data indicates the presence of Marburg Subgroup in the uppermost Mesozoic sequence in some areas which have coal, as demonstrated by some coal exploration holes. Some logs of coal exploration holes in the area of conflict contain considerable sandstone and siltstone above the coal layers and if these sandstones were intersected in water bores it is understandable if they have been interpreted as Hutton Sandstone/ Marburg Subgroup. Where there are no coal exploration bores, coal seam gas wells, stratigraphic holes or other petroleum wells, the water bore data has been taken as the authoritative source and the boundaries drawn on this basis.

In summary, the interpretation of the remote sensed data accompanied by ground truthing and validation assisted in addressing the main objectives of this project:

1. The Eurombah Formation has bed forms similar to the underlying Hutton Sandstone and a higher Th signature than the Walloon Coal Measures which supports the exclusion of this formation from the coal measures.
2. The Durabilla Formation is apparently compositionally more similar to the Walloon Coal Measures and has similar bed forms, however the wireline interpretation undertaken as part of this study did not enable the splitting of the transitional Eurombah and Durabilla formations at the base of the Walloon Coal Measures. Therefore, units described as either Durabilla Formation or Eurombah Formation have been identified as Eurombah Formation.
3. Consequently, the base of the Walloon Coal Measures is herein defined as occurring at the base of the Taroom Coal Measures.
4. The Springbok Sandstone and the other Injune Creek Group formations have been successfully separated based on their radiometric signature and the elevation of the terrain where they crop out.
5. Examination of a large number of water bores in the Condamine Irrigation Area enabled the delineation of the Condamine Basin with its alluvial and colluvial infill, and the underlying Mesozoic bedrock; however, the existing block faulting did not allow for a reliable definition of the Springbok Sandstone and Walloon Coal Measures beneath the Condamine Basin.
6. The methane seeps in the Condamine River occur in an alluvial depocentre and appear to be a consequence of local faulting intersecting the CSG-bearing units below the alluvium.

Recommendations

It is recommended that a further project be implemented to update the younger units of the Surat Basin. This would include the units that have been included in the Kumbarilla beds below the Griman Creek Formation and all the overlying Cretaceous units.

Discussions with the DNRM Regional office in Toowoomba indicate that mapping of the soils and landforms in the western Surat and St George map sheet areas have more detail in the Cainozoic soils than the current geological maps. As these soil units relate to geomorphic processes, further mapping in this area of the Mesozoic units higher in the sequence should utilise this data source to update mapping of these regions. These geomorphic units have a genetic relationship to the geology and should be used in updating the geological mapping on these sheets.

Discussions with Jeff Copley at the University of Queensland who is working with detailed seismic and 3D profiles has developed a range of sections that show significant structural dislocation in the region and these should be incorporated into any new project to help define the structure of the region.

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